Integrated Systems Modeling for Irrigation Expansion at the River Basin Scale

by

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Abstract

Understanding the complexities and quantifying the impacts of expanding irrigation in the presence of ongoing socioeconomic developments, population growth, climate change, and policy factors is a challenging task. Simulation models can facilitate such a task and allow visualizing outcomes; they can thus recommend specific policy reforms or suggest a different policy. However, such tools are often challenged by the need to integrate various processes that operate at different spatial or temporal scales, and by the need to produce models that characterize impacts at scales in which policy decisions are made – typically at river basin scale and over long time periods.

The central theme of this thesis is to capture the complexity of irrigation expansion for policy assessment under climate change using a systems approach, and to find a balance between temporal modeling scales for integrating models that allows long-term agricultural and water policy assessments while maintaining accurate crop modeling. To this end, potential water policies to address water scarcity at the river basin were extracted from the literature to develop a list for modelers as a starting point for integrated modeling and for policymakers for strategic planning. The list has 51 policy interventions for the agricultural water sector, 55 for the municipal, and 31 for the industrial with relevant citations of successful modeling studies. Further, while process-based crop growth models that run on a daily time step are typically superior, knowledge and computational constraints in integrated assessments require a compromise between the temporal scales at which component processes occur, which may be short or long, and the longer scales of interest to decision makers for policy assessment. Moreover, process-based models may rely on fine-scaled data series that are hard to obtain, time-consuming to generate, or that may simply be unavailable. Therefore, a water-driven process-based crop growth model, CropSD, was developed in a System Dynamics framework based on FAO's AquaCrop model to run daily, semi-weekly, and weekly simulations in conjunction with weekly weather input data. The aim was to examine the ability of coarser simulations to reproduce the behavior of a fine-scale model such that it can be integrated into other socioeconomic, environmental, or hydrologic models to broaden the scope of their applications. Model skill for simulating crop biomass and yield and water demands at different simulation time steps was assessed with weekly weather input data for a number of hypothetical farms including barley Alberta in Canada, maize in Nebraska in the US, and potatoes in Brussels in Belgium to represent a range of crops and growing environments. The R^2 statistic showed a value of 0.95 for daily simulations, 0.83 for semi-weekly simulations, and 0.72 for weekly simulations of crop yields. The results suggest that semi-weekly and weekly simulations provided a compromise between accuracy and longer timescale for process-based crop growth model to be used in integrated assessments.

CropSD was then integrated with a socioeconomic system dynamics model to describe the “big picture” of expanding the irrigation sector of Alberta in Canada. The resulting integrated model, Alberta Irrigation Scenario Simulator (AISS), captures the feedback loops between irrigation expansion, and its technical, social, economic, environmental processes, and policy choices. The model was used to simulate the impacts a set of seven scenario groups that covered a range of plausible expansion pathways for Alberta’s irrigation sector. Impacts of climate change, socioeconomic changes, and policy interventions on crop yields, economic returns, irrigation demands, and water withdrawals were assessed. Results showed increasing trends for dry matter crop yields to 2040 for the six major irrigated crops of Alberta with an increase per year of 0.071 t ha^{-1} for alfalfa, 0.04 t ha^{-1} for barley, 0.031 t ha^{-1} for canola, 0.061 t ha^{-1} for potatoes, 0.065 t ha^{-1} for sugar beets, and 0.039 t ha^{-1} for wheat for the high GHG emission climate scenario (RCP 8.5). Irrigation water demands increased by 11% in 2036-2040 based on the expansion plans and policy interventions by the Government of Alberta (GoA) under RCP 8.5. Increasing the reservoirs storage capacity by 5% did not offset the decreased water supply simulated by the SWAT hydrologic model of Alberta in 2035. However, an increase in storage by 10% allowed expansion beyond the goals by the GoA to reach 700,000 hectares.

Preface

The thesis is my original work. It is organized in a journal article format. Each chapter excluding Chapters 1 and 5 is a standalone article for journal submission but integrated into a cohesive unit with a logical progression from one chapter to the next. As such, each chapter has its own introduction, hypothesis, and conclusions. To date, this work has led to the submission of one manuscript for publication in a peer-reviewed academic journal, and two others in preparation for submission. The task of preparing the thesis has been to produce from these activities a single piece of work. For Chapter 2, I was responsible for conducting the literature review, data collection, models' development and programming, analysis of results, as well as the manuscript writing and editing. For Chapter 3, I was responsible for the scoping review, framing the policy tables, analyzing results, and writing and editing the manuscript. Kai Wang provided a number of policy options for the municipal and the industrial water sectors with relevant citations. In Chapter 4, I was responsible for conducting the literature review, data collection, system dynamics model development and validation, analysis of results, as well as the manuscript composition. Dr. Monireh Faramarzi developed and ran the SWAT hydrologic model for Alberta to simulate the future water supply for the irrigation sector of Alberta. My supervisor, Dr. Evan Davies contributed to manuscript composition and editings for all chapters and provided insights and recommendations on the system dynamics model development. Finally, Chapter 1 provides a general introduction to the thesis, and Chapter 5 summarizes and concludes this research, and presents recommendations for future work.

Some of the research conducted for this thesis forms a part of a research project led by Dr. Evan Davies as the principal investigator, which received ethics approval from the University of Alberta Research Ethics Board, under the project name of “Systems modelling for sustainable land and water policy in Alberta's irrigation”, No. Pro00044808, December 23, 2013.

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Edmonton, AB, Canada

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To…

My beloved mother

My father who has always been my inspiration

My sincere wife, Mohga

My beautiful daughter, Gamela

My sister, Dina, and my brother, Mostafa

For all their love, support, and patience

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I would like to thank my supervisor, Dr. Evan Davies, for giving me the opportunity and support to be his second PhD student — he ensured that I exercised my potential and stretched my boundaries in scientific thinking and academic writing. I would like also to extend my gratitude to the members of my supervisory committee: Dr. Simaan Abourizk, and Dr. Mark Loewen for their valuable comments and suggestions, as well as my examination committee: Dr. Jan Franklin Adamowski and Dr. Amit Kumar.

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Above all, I am forever indebted to my mother for her continuous support, prayers, and love, and to my amazing wife, Mohga, for all her patience, encouragement, understanding, and scarifies during my studies. Thank you to my fellow graduate students, and particularly Amr Gharib, Mohamed Gaafar, and Maged Gouda for their endless help and encouragement to overcome doubts and difficulties I occasionally faced.

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Chapter 1. Introduction

This research describes the Alberta Irrigation Scenario Simulator (AISS), a new process-based integrated systems model for simulating irrigation expansion at the river basin scale. The result is an improved characterization of the feedback mechanisms between policy choices and socioeconomic, technical, and environmental processes in the context of irrigated agriculture and under climate change.

Simulations using AISS identify both the capacity of Alberta's irrigation sector to future expansions and its leverage points. The model assesses the sustainability of Alberta's irrigation sector with intentions of expansion and under a range of policy interventions to the year 2040.

1.1 Research Motivation

Managing our water resources has become more difficult in recent years owing to the ever-growing population and its increasing demands for water, food, and energy compounded by climate change which is likely to alter precipitation, evapotranspiration patterns, and river flows (Gizaw and Gan, 2016; Mishra et al., 2017; Siam and Eltahir, 2017; Steele et al., 2018; Tariku and Gan, 2018). For instance, water scarcity threatens more than four billion people globally at least one month every year, with one-eighth of that number living under severe scarcity year-round (Mekonnen and Hoekstra, 2016).

Globally, irrigation water accounts for more than 70% of the total freshwater withdrawals (FAO, 2016). Irrigation reduces poverty (Dillon, 2011; Smith, 2004), increases food security and contributes to affordable food prices (Kadiresan and Khanal, 2018; Liu et al., 2017), and improves health and nutrition outcomes (Domènech, 2015; Rosegrant et al., 2009).

However, it is also a significant player in river basin-level competitions for water (see Figure 1.1). It competes with cities, industries, and reservoirs' recreational activities, and challenges the capacity of water resources to ensure socioeconomic development and ensure future food security in an environmentally and socially sustainable manner.

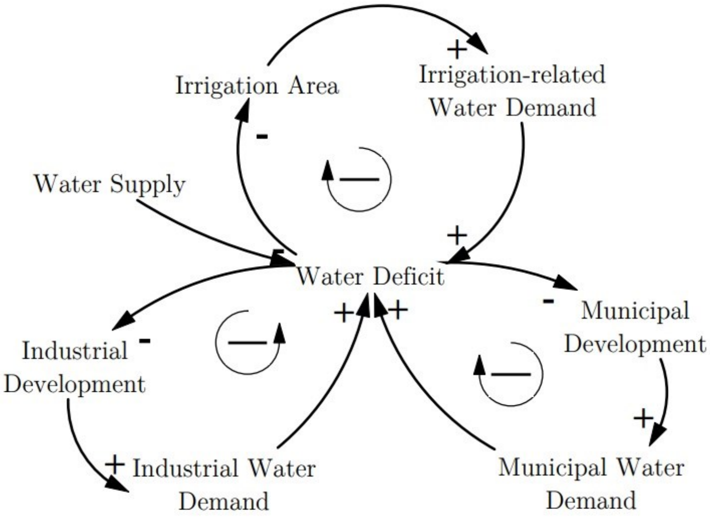

Figure 1.1. A map of the intersectoral water competition between the agricultural, municipal, and industrial sectors.

Irrigation expansion, water security, and food security are intrinsically linked. Water security is defined as "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments and economies." (Grey and Sadoff, 2007, p.545), and food security is defined as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 2002). They are multi-dimensional concepts which incorporate physical and social dimensions of water availability, water use, and food production, and they are direct outcomes of a sustainable irrigated agriculture system, which in turn contributes to both water and food security in the form of feedbacks (see Figure 1.2). Consequently, understanding that complex nature and the dynamic linkages to irrigation should not be understated or ignored.

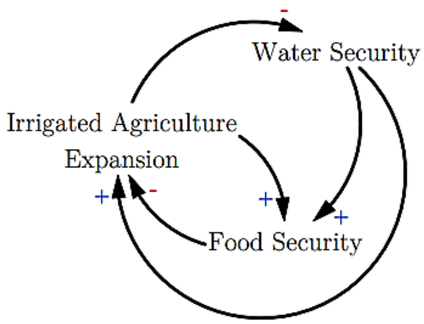

Figure 1.2. Feedback loops between the expansion of irrigation and water and food securities

Here enter computer models that aim to apply narrower definitions of such concepts and use practical applications to aid precise identification and assessment of specific food and water security concerns and to identify potential policy trade-offs (Cook and Bakker, 2012). Without the careful development and evaluation of such potential policies on a river basin scale, both water and food insecurities will persist and may worsen in the future. However, first, the literature falls short in providing a comprehensive catalog of policy options for water resources users in a river basin which is arguably the fundamental unit of water management (Gregory, 1999; Jury and Vaux, 2007; Mitchell et al., 2014). Second, the human-environment interactions are complex, poorly understood, and unpredictable. As such, evaluation of the complex interactions and trade-offs for irrigation expansions between policy choices and socioeconomic, technical, and environmental processes is challenging to achieve, but imperative. On water policies, Cosgrove and Loucks (2015, p.4836) noted that:

> *"improving our governance policies and procedures takes even more time than obtaining the funding needed to improve our infrastructure systems."*

Perhaps the reason is the lack of understanding of policy options, and particularly confidence in projected outcomes. Further, while natural systems, e.g., agriculture, are managed at the field- or landscape-scale, policies are set at a river basin scale or provincial levels (Bhave et al., 2018; Rajagopalan et al., 2018).

It is often thought that models are platforms to find the best alternative from an array of options for a specific objective (or multiple) and subject to constraints. In reality, humans do not often behave optimally, and therefore the traditional approach in computer modeling of water resources systems– which aimed at obtaining the best solution (i.e., optimization) – is not usually the most suitable option for water management, and it does not necessarily reflect the human mindset (Kuil et al., 2018). Instead, simulation models facilitate the analysis of policy options through integrated systems applications (e.g., Capalbo et al., 2017; Ferrández-Villena and Ruiz-Canales, 2017; Jones et al., 2017; Lundström and Lindblom, 2018; Voinov and Shugart, 2013). These models aim to clarify policy implications and quantify their potential effects. They also permit visualization of outcomes and thus can help to identify specific reforms or suggest new interventions.

Irrigated agricultural systems are complex dynamic systems – see Figure 1.4. Policy assessment in irrigated agriculture often requires multi-year simulations, and background changes in the socioeconomic conditions that affect irrigation production can take years to become evident – for example, incremental changes in infrastructure, technology adoption time frames, delays in decisions of farmers/policymakers, population growth in nearby cities, and climate change effects. Such limitations have been tackled using simulated results from established crop growth models to develop statistical crop production response curves as inputs to other models (Claessens et al., 2012; García-Vila and Fereres, 2012); however, such models lack the ability to capture the simultaneous feedback relationships (Ewert et al., 2015) that connect crop growth to the whole irrigated agricultural system of plants, soil, climate, water, infrastructure, and people. Moreover, these developed crop production response curves cannot be applied to extrapolate responses that are outside their "estimation domains", or the historical data used to construct the curves (Jones et al., 2017b), and therefore they are ill-suited to study the effects of increasing atmospheric CO_2 concentrations or long-term changes in temperatures on crop yields and water demands (Basso et al., 2015). In short, they are not suitable for climate change impact assessments. Since that approach is inappropriate for policy assessment for the future (see Chapter 2), integrated process-based systems models (see Chapter 4) offer the best means of improving understanding of the larger irrigation expansion context, of highlighting feedbacks between irrigation expansion and its drivers (recall Figure 1.4), of analyzing proposed policy interventions, and of proposing new policy measures that would otherwise be ignored or overlooked.

1.2 System Dynamics Methodology

System dynamics (SD) is a systems thinking method that is used to deal with complex, dynamic systems (Forrester, 1961; Sterman, 2000). Models produced with SD clarify the behavior of a complex system and its responses to interventions over time (Winz et al., 2008). They are intended to increase understanding of the unpredictable effects of feedbacks between subsystems, whose behavior would otherwise be assumed or ignored (Davies and Simonovic, 2011; Elsawah et al., 2017). They can be used to connect socioeconomic changes with natural systems, and permit simulation of the effects of policy interventions on an entire system (Davies and Simonovic, 2010; Gunda et al., 2018; Wang and Davies, 2018). Therefore, system dynamics modeling approach is well-suited to policy assessment in irrigated agricultural modeling. Figure 1.3 shows the output of a series of questions developed by Kelly et al. (2013) for the choice of the most appropriate methodology based on the reason for modeling, which recommended the use of system dynamics.

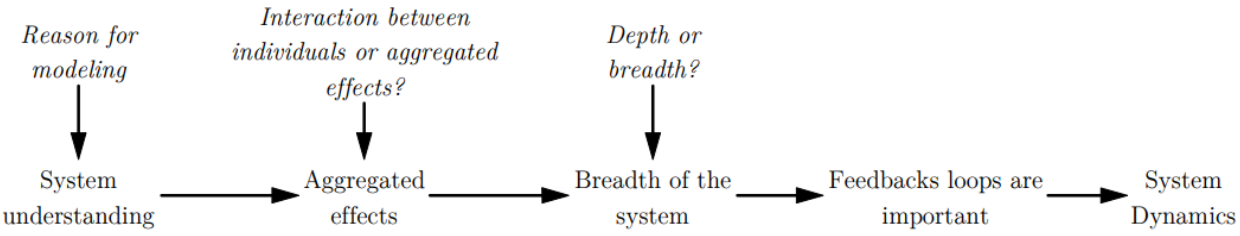

Figure 1.3. The pathway adopted from the decision tree of holistic modeling approaches described by Kelly et al. (2013)

A causal loop diagram (CLD, as the one shown in Figure 1.4) is an essential tool of system dynamics methodology and is often developed with participation from stakeholders (Inam et al., 2015). It represents the causal relationships or connections between two variables in a system. CLD produces explicit, graphical “maps” of our mental models of a system structure, thus improves the understanding of interactions between the elements of a complex system and its various subsystems. It communicates our understanding of the system to others. That focus on qualitative representation, and on identification of feedbacks, makes CLDs to be considered as conceptual models (Mirchi et al., 2012; Winz et al., 2008) that communicate both the characteristics of subsystems and stakeholders' perspectives; capture hypotheses about the causes of dynamics; and show the feedback loops that affect the behavior of various system elements and its key variables (Sterman, 2000). In short, a CLD represents a holistic understanding of the system's structure, sets its boundaries, and identifies the key variables that contribute to the dynamics of a system (Inam et al., 2015; Pahl-Wostl, 2017; Simonovic, 2009). Note that because a CLD is qualitative, it cannot be used to determine the behavior of a system, such as projected changes in values of variables, the dominance of different loops, or the likely outcomes of altering model parameters. It shows possibilities, not outcomes since it is not a numerical model. Quantification of the system requires simulation through the development of Stock and Flow Diagrams (SFD) and their associated equations, which help to clarify how a system works, or "behaves," and how we can intervene in the system to make it behave more beneficially.

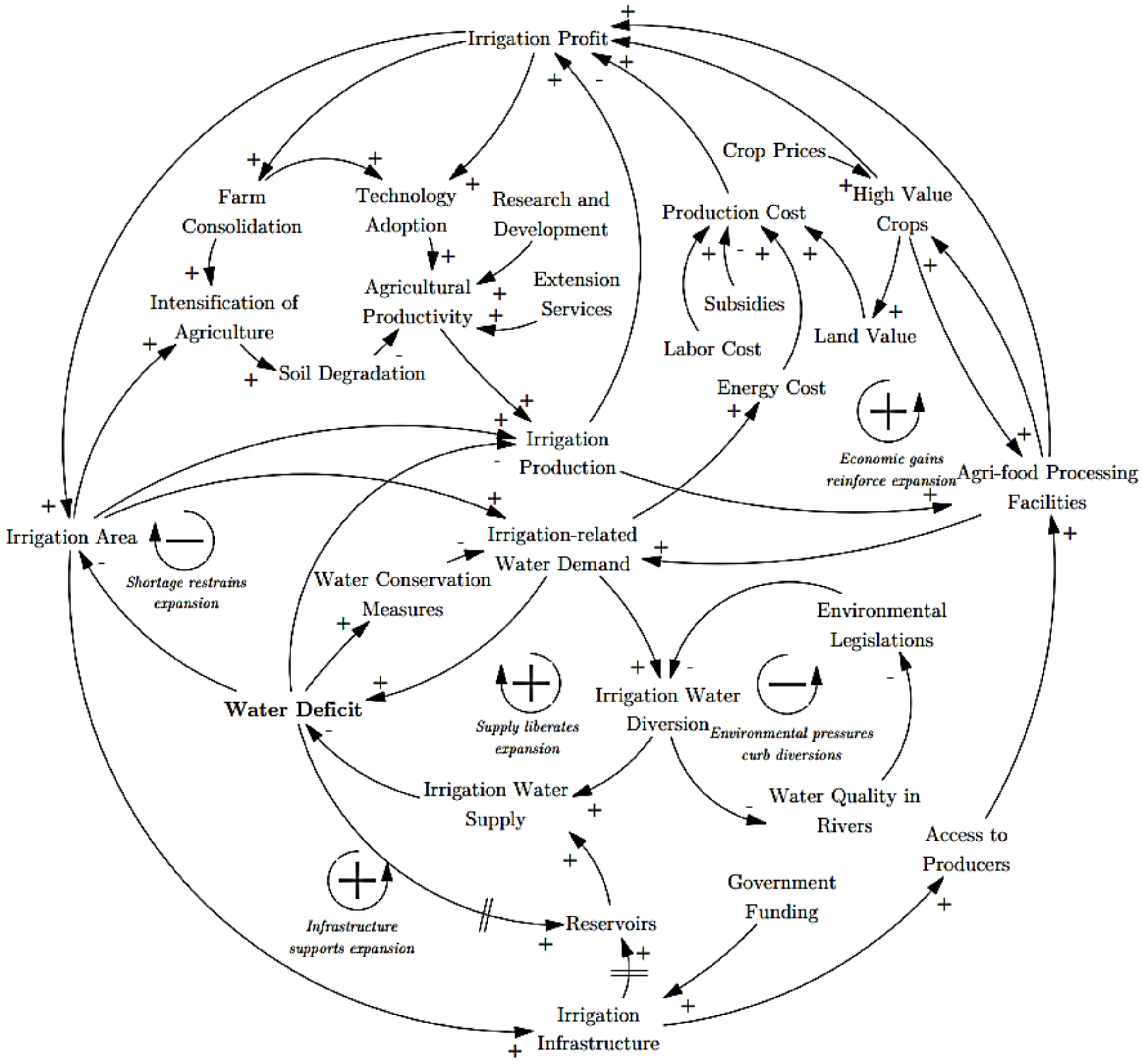

Figure 1.4. High-level summary of the dynamics describing an irrigated agricultural[1].

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[1] Two variables linked by an arrow are independent and dependent variables, and a change in the independent variable causes a change in the dependent variable. Arrows are assigned polarities, either positive (+) or negative (-). For example, a negative link means that if the value of the independent variable increases (decreases), the value of the dependent variable decreases (increases), while a positive link means the variables increase (decrease) together. Connections between two variables can expand to form loops through a network

1.3 Agricultural Models

1.3.1 Process-based crop growth models

Crop yield response to water is a core element of any decision making for agricultural models. Crop growth models are used to estimate possible crop yields based on water application and its timing, weather conditions, and agronomic practices. Their development spans five decades and was initiated by C.T. de Wit, who described the photosynthesis of leaf canopies (de Wit, 1965). Since then, a variety of process-based crop models has been developed to simulate yield as well as crop development throughout their growth cycle (Ascough II et al., 2008). Many models are available with various levels of accuracy, applicability, and types of crop growth engines as presented in Table 1.1.

Process-based crop growth models can generally be classified based on their crop growth-engine mechanism and the hierarchy of the processes involved in plant growth into three categories: (1) carbon-driven, (2) radiation-driven, and (3) water-driven. Steduto (2003) describes their characteristics, differences, and advantages and disadvantages. Water-driven models express the relationship between cumulative crop biomass and transpiration using a water productivity constant, WP, that is a crop-specific constant parameter (Steduto et al., 2012). Such models are more suitable for irrigation and water use assessments than carbon- or radiation-driven models (van Ittersum et al., 2003). Moreover, the WP parameter of the

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of connections; such loops are called "feedbacks," which have mainly two types: reinforcing (positive) loops and balancing (negative) loops. Reinforcing feedback loops are considered the drivers of a system, whose behavior is characterized by continuous trends of growth or decline. Balancing feedback loops have a target-oriented behavior, such that positive feedbacks driving the system away from a steady state may be balanced by a negative feedback that acts to *neutralize* the effects of the positive feedback water-driven models is distinguished by its low sensitivity to water and salinity stresses (Steduto et al., 2000) and by the simplicity in its formalization and parameterization. Examples of widely-used and well-established crop growth models are provided in Table 1.1, including their inputs and essential outputs, the capacity to model climate change impacts, spatial and temporal scales, and the crop growth engine used (i.e., water-driven, carbon-driven, or radiation-driven). It can be concluded from Table 1.1 that the crop growth models available have been initially developed to be applied at the field scale, which makes them less suitable for “the big-picture” analysis proposed here.

Table 1.1. Comparison of Different Crop Growth Models

Model	Inputs	Key Outputs	Scale	Climate Change	Growth Module
APSIM (Keating et al., 2003)	Daily weather data, soil characteristics and crop management actions	Crop yield responses to climate, genotype, soil and management factors and long-term consequences on the soil	Multi-field, multi-crop simulation; daily time step; multiple crop cycles simulations	Supported	Radiation-driven
AquaCrop (Geerts et al., 2009)	Daily weather data, crop data, soil properties, field management data	Crop development and yield, soil water balance, crop transpiration, aboveground biomass, irrigation scheduling, and soil salinity	Field-scale, single crop simulation; daily time step	Supported through projected temperature regimes and elevated CO2 concentrations	Water-driven
CropSyst (Stöckle et al., 2003)	Location, soil properties, daily weather data, crop parameters (40 parameters), and field management conditions	Soil water budget, soil-plant nitrogen budget, biomass production and crop yield, residue production and decomposition, soil erosion by water, and soil salinity	Daily time step; multi-crop multi-year simulation	Supported by CO2 concentration increases	Water- and radiation-driven
DSSAT (Jones et al., 2003)	Field conditions and location, daily weather data, soil characteristics, crop data, and field management data	Crop growth, development, and yield, changes in soil water, carbon and nitrogen soil balance	Field-scale (homogeneous soil conditions) multi-year; single crop; daily time step	Supported	Modular approach using different template modules for different crop types
EPIC (Williams, 1990)	Soil properties, daily weather data, crop parameters, nitrogen and carbon applications	Decisions involving drainage, irrigation, crop yield, erosion (wind and water), soil water balance, nutrients and nitrogen soil dynamics	Field and global scale; multi-crop; multi-year simulation; daily time step	Supported	Radiation-driven
RZWQM2 (Ahuja et al., 2000)	Daily weather data, initial soil water and chemical profiles, and crop management	Plant growth and yield, water movement and balance in the soil profile, chemical transport, and nitrogen/carbon dynamics	Daily time step; multi-crop, multi-year simulation	Supported through elevated levels of CO_2 and specifying future climate data	Carbon- and radiation-driven (built-in generic crop growth module or recalls DSSAT-CSM)
STICS (Brisson et al., 2003)	Daily climatic data, soil (water and nitrogen initial profiles and permanent soil features) and crop management	Crop growth and yield, soil water and nitrogen balance	Daily time step, single crop multi-cycle simulation, and runs on a field scale	Supported through elevated levels of CO_2 and projected climate data	Radiation-driven
WOFOST (Supit et al., 1994)	Climate data, soil moisture content at various suction levels, and site-specific soil	Soil water balance crop development and yield and variability for different climate scenarios.	Daily time step, site-specific	Supported	Carbon-driven

	and crop management data

1.3.2 Long-standing problems in integrated agricultural models

Agricultural models have increasingly been applied in integrated, multidisciplinary studies related to climate change assessment and adaptation (Aurbacher et al., 2013; Bassu et al., 2014; Ewert et al., 2015; Lehmann et al., 2013), food security (Godfray et al., 2010; Tubiello and Ewert, 2002), mixed crop-livestock systems (Tendall and Gaillard, 2015; Thornton and Herrero, 2001; Tracy and Zhang, 2008), and agricultural and water policy assessment (Bryan et al., 2011; García-Vila et al., 2009; García-Vila and Fereres, 2012; Therond et al., 2009). However, there are several challenges to the development of irrigated agriculture systems models for policy assessment. These include the:

1. Need for an integrated modeling approach that captures the feedbacks between and within various components of agricultural and water systems explicitly,
2. Use of a linear sequential approach to model integration, where one model completes its execution and produces data for the subsequent model, as opposed to iterative,
3. Depth of the problem rather than the breadth being prioritized,
4. Lack of clearly defined boundaries for the problem, and
5. Lack of code or model reusability.

Integrated agricultural models could help to improve the understanding of the underlying causes of changes and the possible trade-offs in an irrigated agriculture system in response to policy changes. However, producing an adequate characterization of the feedback mechanisms among the various components is a challenge. The importance of systems and the interactions of the various components that make up the system are often stressed and recommended; however, attempts to address such complex systems through integrated assessment is to couple independently-developed models in a linear manner that applies one model's output as the next model's input. Additionally, it is often the depth of the problem that modelers/researchers spend more time on and devote energy to those aspects in which they are most knowledgeable. They then leave the other components or the integration between the components marginalized (see Peckerar, 2004). Further, the lack of clearly defined boundaries that describe the extent of the model applicability can often lead to the models being used to answer questions they were not designed for. Moreover, code reusability is often not a priority for model developers and thus expanding functionality outside the domain of the original code/model developers is always a challenge, if not impossible. For example, Holzworth et al. (2015) stated that most models rely on legacy code written using procedural languages. While the models still perform well, they have not been redeveloped in modern coding languages, and most young programmers are not familiar with them.

All these reasons argue for a systems approach that can model irrigated agricultural systems and capture the broader picture of irrigation expansion for future policy assessment.

1.4 Research Objectives

The purpose of this research is to model irrigated agricultural systems in the presence of feedbacks between policy choices and socioeconomic, technical, and environmental factors. It aims also to allow future policy assessment in the context of irrigation expansion and under climate change. The resulting model emerges as a useful tool for identifying policy synergies and trade-offs from stakeholders' knowledge and interests.

The objectives of the research are to:

1. Identify potential policy interventions for basin-level competition over water resources,
2. Find a balance between modeling scales for integration that allows long-term policy assessment while maintaining accurate crop modeling,
3. Capture the complexity of irrigated agriculture in a systems model for policy assessment,
4. Reveal the broader consequences of expanding Alberta's irrigation sector, and
5. Assess the possible impacts of climate change and policy interventions on Alberta's irrigation expansion.

A case study was the irrigation sector of Alberta, Canada. It represents 65% of the total irrigated area in Canada and is concentrated in the southern part of the province, particularly in the South Saskatchewan River Basin (SSRB). The basin has a semi-arid climate with annual precipitation between 200 mm and 500 mm (Martz et al., 2007). To this end, irrigation expansion related questions that are of interest include,

- What is the capacity of the existing irrigation sector under current agronomic, structural, and socioeconomic characteristics to future climate?
- What is the outlook for the irrigation sector under different expansion scenarios, socioeconomic changes, and policy interventions in the presence of climate change?

The first objective involves answering the question of "*What are the available water policies to address potential water shortage in a river basin?*". This objective addresses a gap in the literature on the existence of a list for modelers and policymakers for adaptation measures in agricultural, municipal, and industrial water sectors.

For the second objective, the daily simulation time step used in most process-based crop growth models seems to be the most suitable for crop growth and soil water and nutrients modeling. However, the practicality of policy assessment in agricultural systems tips the balance in favor of a coarser modeling time-step. The difficulty in defining a temporal scale that balances the short time steps necessary for accurate crop modeling and the typically longer timelines of policy assessment for agricultural systems is addressed in Chapter 2. Process-based crop models are investigated to address the second objective of the research. In Chapter 2, a water-driven, process-based crop growth model is assessed to simulate crop biomass and yield accumulations, and total crop water demands using daily, semi-weekly, and weekly simulation time steps. The chapter provides insight into the applicability of coarser-than-daily simulation time steps to simulate long-term crop yields in integrated models, and the impacts of aggregated weather input data on yields for a water-driven process-based crop growth model.

The third objective essentially involves developing the dynamic hypothesis of expanding Alberta's irrigation sector and the connections between its socioeconomic, environmental, and human factors and policy choices. A well-developed dynamic hypothesis implies having enough information to begin formalizing the system into mathematical relationships. It builds a conceptual understanding of the system, sets its boundaries, captures hypotheses about the causes of dynamics, and shows the feedback loops that affect the behavior of various system elements, key variables, and critical time delays that may rise unexpected consequences (Mirchi et al., 2012; Simonovic, 2009; Sterman, 2000; Winz et al., 2008)

Fourth and fifth objectives deal with moving the dynamic hypothesis into the formulation of a simulation model (AISS) and its application. The ability of this model to provide insight into irrigated agricultural systems behavior is explored, as well as its capacity to translate this broader understanding into policy assessment. In addition to the capacity of models like AISS to identify dominant feedbacks, its ability to reveal unanticipated consequences in the irrigated agriculture system is expected to be a real strength.

1.5 Research Novelty

The majority of the integrated models for agricultural systems applications are based on sequential, forward feed, data exchange between various models, including those for policy assessment applications. The systems model introduced here integrated a process-based crop growth model with a socioeconomic irrigation expansion model into one model that uses iterative data exchange between its components. This model is built and functions as one whole model, which is new. The model also includes endogenously several features of the real world that are usually modeled as external quantities, such as changes in irrigation areas, water availability, infrastructure changes, and decisions by the irrigation community to expand irrigated area or adopt new technologies. That is important as it describes the feedbacks explicitly and allows iterative data exchange between its different components, such between as infrastructure changes, water availability, land expansion, and effects on crop yields. It goes beyond the single aspect of modeling crop production to understanding the "*big picture*" of irrigation expansion.

1.6 Thesis Outline

This thesis is divided into five chapters, all of which (except the first and last) are formatted as three main contributions and paper submissions to peer-reviewed journals.

Chapter 1 gives a general overview, sets the study in appropriate perspective, and provides the motivation, objectives, and the novel contributions of the research.

Chapter 2 introduces and tests the hypothesis that a process-based crop model can operate with coarser-than-daily simulation time steps of up to weekly in conjunction with aggregated weather input data. It describes a process-based crop growth model developed in a system dynamics framework, called Crop System Dynamics (CropSD), and runs under daily, semi-weekly, or weekly time step with weekly aggregated weather data. This chapter has been submitted for publication to a peer-reviewed journal.

Chapter 3 provides an extensive inventory of water policies intended to address water shortage resulting from population growth and associated socioeconomic development, short- and long-term droughts, climate change, competition between different water sectors as in the paradigm of Integrated Water Resources Management, in which multiple aspects of water supply and demand are considered. The chapter addresses the three main water users: agriculture, municipalities, and industry. It also presents examples from the literature of studies that quantified the effects of the various policies. This chapter is in preparation for submission to a peer-reviewed journal.

Chapter 4 presents the Alberta Irrigation Scenario Simulator (AISS) that integrates CropSD from Chapter 2 with a socioeconomic system dynamics model for Alberta's irrigation sector and policy choices from Chapter 3 to understand and quantify the effects of socioeconomic changes and policy interventions compounded with climate change. It provides an outlook for the irrigation sector of Alberta to 2040. This chapter is in preparation for submission to a peer-reviewed journal.

Chapter 5 concludes the thesis. It provides an overall research summary and principal conclusions of the study. It also sets recommendations for future research of this type of analysis. Each chapter has its own references. Appendices from all chapters are combined and presented after the Chapter 5. Four appendices are included in the thesis. Appendix A provides a detailed model description, use guide, and code required to reproduce the model. Appendix B and C are the supporting material for Chapter 2 and Chapter 3, respectively. Appendix D is the supporting material for Chapter 4.

Chapter 2. On the accuracy of crop production and water requirement calculations: Process-based crop modeling at daily, semi-weekly, and weekly time steps for integrated assessments

2.1 Introduction

Agricultural models have increasingly been applied in integrated, multidisciplinary studies related to climate change assessment and adaptation (Aurbacher et al., 2013; Bassu et al., 2014; Ewert et al., 2015; Lehmann et al., 2013), food security (Godfray et al., 2010; Tubiello and Ewert, 2002), mixed crop-livestock systems (Tendall and Gaillard, 2015; Thornton and Herrero, 2001; Tracy and Zhang, 2008), and agricultural and water policy assessment (Bryan et al., 2011; García-Vila et al., 2009; García-Vila and Fereres, 2012; Therond et al., 2009). See Holzworth et al. (2015) and citations within for a review of further applications. This breadth of applications represents,

- Recognition of the interconnectedness of systems that were typically treated independently in the past (Jones et al., 2017a; Reidsma et al., 2018), and increased effort to identify and solve complex, integrated problems;
- Increased capabilities of computer systems (Capalbo et al., 2017; Ferrández-Villena and Ruiz-Canales, 2017; Lundström and Lindblom, 2018),
- Advances in the state of modeling natural systems (Faramarzi et al., 2017), human behavior (Binks et al., 2016; Turner et al., 2016b), and the connections between them (Davies and Simonovic, 2011; Inam et al., 2017a; Kotir et al., 2017), and,

- Increased understanding of climate change and its effects on ecosystems and human well-being (Faramarzi et al., 2013; Gosling and Arnell, 2016; Myers et al., 2017; Pecl et al., 2017).

Integrated models are crucial for evaluating, and potentially understanding, complex interactions and trade-offs among policy choices and socioeconomic, technical, and environmental processes (Kelly et al., 2013); further, such models typically require long simulation periods – from multi-year to multi-decadal – to permit long-term impacts to emerge and accumulate. Agricultural models use crop growth modules as the core component to predict crop response to varying climatic and agronomic conditions. Such models range in complexity from simple empirical relationships to highly-complex, process-based crop growth models (as presented in section 2.2). In integrated assessments, there is value in simplicity (Letcher et al., 2007; Voinov and Shugart, 2013; Wieland and Gutzler, 2014). While process-based models are typically superior, knowledge and computational constraints in integrated assessments usually require a compromise between the temporal scales at which component processes occur, which may be short or long, and the longer scales of interest to stakeholders (Kelly et al., 2013). Further, process-based models may rely on fine-scaled data series that are hard to obtain, time-consuming to generate, or that may simply be unavailable. As an alternative, however, coarser temporal resolution weather input data may produce similar model results, and the corresponding longer simulation time steps may reduce both data collection costs and model execution time. The effects on crop model performance (i.e., crop yields) of using longer model time steps or aggregated weather input data have not been established, with only a limited number of studies conducted (Lorite et al., 2005; van Bussel et al., 2011).

These observations lead to the two hypotheses of this study: (1) that temporally aggregated input data provide acceptable results for crop models used in multidisciplinary policy assessment studies, and (2) that longer than daily simulation time steps for crop modeling provide sufficiently accurate results to represent the key functional responses of a crop model – for example, the end of season biomass or yield, or seasonal water requirements – for the same studies. To test the hypotheses, we apply a water-driven, process-based crop growth model to simulate crop biomass and yield accumulations, and total crop water demands, for three crops and locations, using aggregated weather input data and daily, semi-weekly, and weekly simulation time steps. The aim of the study is to provide insight into the applicability of coarser-than-daily simulation time steps to simulate long-term crop yields in integrated models, and the impacts of aggregated weather input data on yields for a water-driven process-based crop model.

2.2 Crop Production Modeling Approaches

Crop models can be categorized as statistical crop models – those derived by fitting a function to predict crop yield from historical observations over multiple years – and mechanistic crop models, which are process-based models with functions that describe the various processes of crop growth with a high level of detail. Statistical crop production response models (e.g. production functions) can be used as inputs to broader spatial and/or temporal scale studies that involve long-term biophysical or socioeconomic components. Further, they can be coupled relatively easily to other economic or hydrologic models to provide insights on historical trends of crop yields, for example. However, these “reduced form crop models” (Jones et al., 2017b) are often developed to represent local agronomic and environmental conditions (Bennett et al., 2014; Keating et al., 2002; Prasad et al., 2006) and their development depends on long historical data records of crop yields and climate or water variables (Lobell, 2013; Lobell and Burke, 2010). Thus, they cannot be applied with confidence to extrapolate responses that are outside their estimation domain (Jones et al., 2017b), and further they cannot capture the effects of increasing atmospheric CO_2 concentrations or long-term changes in temperature on crop yields (Basso et al., 2015).

As an alternative to statistical models, process-based crop models provide an accurate representation of crop-yield responses to weather, soil moisture and nutrient contents, and to agronomic practices. They use deterministic functions that describe cause-and-effect relationships between crop yields and external drivers. A number of dynamic process-based crop models have been developed, many of which are both widely-used and well-established. Such models include APSIM (Holzworth et al., 2014; Keating et al., 2003; McCown et al., 1996); FAO's AquaCrop (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2012, 2009); CropSyst (Stockle et al., 1994; Stöckle et al., 2003; Stöckle and Nelson, 2000); DSSAT (Jones et al., 2003, 2001); EPIC (Sharpley et al., 1990; Williams, 1990, 1989); RZWQM2 (Ahuja et al., 2000); STICS (Brisson et al., 2003, 1998); and WOFOST (Diepen et al., 1989; Supit et al., 1994). Many more models are also available; see Rivington and Koo (2010) and Di Paola et al. (2016) for surveys of process-based crop modeling tools.

Process-based crop growth models are often resource-intensive in terms of both input data and simulation time (Adam et al., 2011; Jones et al., 2017a); however, they are the only suitable tool for quantitative assessment of future crop productivity (van Bussel et al., 2011). Consequently, their coupling to other socioeconomic, environmental, or hydrologic models through integrated modeling efforts is inevitable, despite the fact that such integration is challenging and time consuming, and also typically requires skilled modelers and programmers because of differences in the temporal and spatial scales of the models, and reliance on legacy modeling approaches that are difficult to integrate (Hamilton et al., 2015; Holzworth et al., 2015; Malard et al., 2017). A common approach in integrated assessment is to couple independently-developed models in a linear manner that applies one model's output as the next model's input (Belete et al., 2017). Where crop models are to be used in this fashion, the skill of process-based modeling with coarser-than-daily simulation time steps has not been studied and is seldom noted in the literature. We believe this "gap" can be attributed to the absence of process-based models that operate with coarse time steps, and perhaps a lack of awareness that accurate results are obtainable with simulation time steps larger than daily for integration purpose.

2.3 Materials and Methods

We adapted the water-driven FAO's AquaCrop crop growth model to a system dynamics framework (SD; Forrester, 1961; Sterman, 2000) and revised the calculation routines from AquaCrop's daily time step to a flexible version able to run in daily, semi-weekly, or weekly simulation time step settings (see supporting information in Supplementary Material sections S4 and S5). Called here CropSD, this revised version allows:

1. Testing of the performance of a water-driven process-based crop model for weekly aggregated weather input data, rather than the typical daily input of AquaCrop, to ensure that the model can accurately reproduce crop biomass and yields; and
2. Examination of model performance under a range of soil moisture conditions, and investigation of simulated crop biomass production and crop yield to different simulation time steps – specifically daily, semi-weekly, and weekly.

Note that our aim is not the development of a new model to replace existing, well-established crop growth models, but to rather test the effects of alternative time steps and levels of data aggregation on a process-based crop model for integrated assessment purposes.

2.3.1 AquaCrop: The selection of a process-based model and its growth mechanism

FAO's AquaCrop (v5.0) daily model was chosen because of, 1) the relatively small number of inputs compared to the other models, 2) the availability of documented equations, 3) the use of a water-driven growth engine (Steduto, 2003; Steduto et al., 2012) that is well-suited to conditions where water can be a limiting factor in crop production (van Ittersum et al., 2003), and 4) its popularity for crop modeling applications. AquaCrop has been used to quantify the effects of various water regimes and agronomic and climatic conditions on crop growth and yield (Andarzian et al., 2011; Araya et al., 2010; Evett and Tolk, 2009; García-Vila et al., 2009; García-Vila and Fereres, 2012; Geerts et al., 2010; Hussein et al., 2011; Mkhabela and Bullock, 2012). Its performance has been evaluated, revealing reliable performance and accurate results in simulating crop growth and yield and water requirements both against other well-established models (Abedinpour et al., 2012; Abi Saab et al., 2015; Battisti et al., 2017; Confalonier et al., 2016; Pereira et al., 2015; Todorovic et al., 2009), and against field experiments for various crops (Farahani et al., 2009; Heng et al., 2009; Iqbal et al., 2014; Stricevic et al., 2011; Wellens et al., 2013; Zeleke et al., 2011). More recently, AquaCrop has been reproduced in an open-source (AquaCrop-OS) Matlab (Mathworks Inc., 2015) format to allow parallel execution of the model, thus reducing run times when large numbers of simulations are needed; see Foster et al. (2017) for details.

AquaCrop separates non-productive soil evaporation from productive crop transpiration, and estimates crop yield by multiplying the biomass by the harvest index (HI) (Raes et al., 2009; Steduto et al., 2012, 2009). It uses thermal time, or growing degree days (GDD), as its default clock and runs with a daily time step. Leaf development in the model is expressed through the canopy ground cover, which is the fraction of the soil surface covered by the canopy. The canopy cover is then used as the basis of actual crop transpiration calculations. The model derives the crop biomass from the amount of water transpired (Tr) by the crop using a conservative water productivity parameter (WP*), normalized for atmospheric evaporative demand ET_o and air CO_2 concentration, and is thus applicable to diverse locations and climate conditions, including future climate scenarios (Raes et al., 2006).

2.3.2 Model scenarios

To address our two hypotheses, a number of test simulations were performed with CropSD to assess the effects of three alternative simulation time steps with weekly weather input data, as compared with daily simulations with daily input data in AquaCrop. These simulations focused on three crops in three different regions – barley in Alberta (two locations), Canada, maize in Nebraska, USA, and potato in Brussels, Belgium. Four irrigation practices and ten growing seasons were selected to reflect a range of climatic conditions and soil moistures at different stages of crop growth, as typical for long temporal-scale applications. Irrigation applications were triggered by the percentage of water depleted from the root zone, ranging from 20 to 100 percent (Table 2.1) of the total available water (TAW) between field capacity and permanent wilting point for each location.

Table 2.1. Characteristics of the four irrigation treatments.

Treatment	Allowable depletion (%TAW)
T20	20%
T40	40%
T60	60%
T100	100%

For Alberta, representative barley farms at Enchant (50° 10’ N, 112° 26’ W, 811.61 m asl) and Fincastle (49° 48’ N, 112° 3’ W, 803.96 m asl) were simulated over a 10-year period (2006-2015), using the input parameters described below. Barley is grown on about 10% of the total irrigated area of Alberta (AAF, 2017), making it the fourth most-commonly grown irrigated crop in Alberta. Weather input data were obtained from the Alberta Weather Data Viewer of Alberta Agriculture and Forestry (AAF, n.d.). Station records provided daily maximum and minimum temperatures, wind speed measured at 2 m, relative humidity, and solar radiation. The regional climate is characterized as cold semi-arid, with average annual precipitation values for the study period of 333 mm in Enchant and 370 mm in Fincastle. Soil properties were obtained from the Agricultural Region of Alberta Soil Inventory Database (AGRASID, 2013), which contains a collection of soil polygons with all the necessary soil input information. Model data requirements included soil horizon thicknesses; and soil properties, comprising soil water content at saturation (SAT), field capacity (FC), permanent wilting point (PWP), and saturation hydraulic conductivity (Ksat). Soil data for the two sites are summarized in Table 2.2. Initial soil moisture conditions under all scenarios were set equal to field capacity. Further, because precipitation data were aggregated to a weekly time scale (see Figure 2.1 for example at Enchant of the weekly precipitation and mean temperature inputs compared to their daily counterparts in 2006), Curve Numbers (CN) were not corrected for soil wetness; therefore, one CN value was used that corresponded to Antecedent Moisture Class II (Raes et al., 2012). A CN value of 61 was assumed for all simulations and assigned to the soil configuration of AquaCrop.

Table 2.2. Soil characteristics for the study locations

Layer	Texture	Thickness (mm)	Soil water content			Ksat (mm/day)
			Saturation ($m^3.m^{-3}$)	Field capacity ($m^3.m^{-3}$)	Wilting point ($m^3.m^{-3}$)	
Enchant, Alberta						
1	Loam	100	0.46	0.31	0.15	250
2	Silt loam	100	0.46	0.33	0.13	250
3	Loam	300	0.47	0.33	0.18	150
4	Clay loam	2000	0.49	0.41	0.22	15
Fincastle, Alberta						
1	Loam	200	0.53	0.29	0.16	250
2	Loam	100	0.47	0.29	0.17	250
3	Silt loam	400	0.47	0.33	0.18	150
4	Silty clay	300	0.49	0.41	0.22	15
5	Silty clay	800	0.49	0.39	0.22	15

Barley input parameters were modified based on AquaCrop's default barley file, which contains both site-specific and conservative (i.e., constant) parameters for the crop. Site-specific parameters were set to local conditions based on Langhorn (2015), who calibrated the various stages of crop phenology, including the growing degree days from seeding to emergence, the start of flowering, maximum rooting depth, senescence, and maturity. All crop input parameters used are summarized in Table 2.3. Similar data were obtained for the other two study locations for maize in Nebraska, US and potato in Brussels, Belgium, and are described in sections S2 and S3, respectively, of the supplementary material.

Table 2.3. Summary of crop parameters for Barley, as adjusted and calibrated to local conditions in southern Alberta.

Parameter	Symbol	Value	Unit	Source *
Growth				
Water productivity	WP	15	$g.m^{-2}$	d
Stomatal closure upper threshold	p_{sto}	0.6		d
Shape factor for stomatal closure		3		d
Morphology				
Canopy cover per seedling at 90% emergence	cc_0	1.5		AAF
Number of plants per hectare		3,000,000		AAF
Canopy growth coefficient	CGC	0.008114	% $degree\text{-}day^{-1}$	c
Maximum canopy cover	CC_x	80	%	a
Maximum rooting depth	Z_x	1.3	m	
Shape factor describing root zone expansion		1.5		d
Canopy decline coefficient at senescence	CDC	0.00571	% $degree\text{-}day^{-1}$	c
Crop coefficient for transpiration	$K_{cTR,x}$	1.1		d
Decline of crop coefficient from ageing	f_{age}	1.05	% day^{-1}	d
Upper threshold of water stress for canopy expansion	$p_{exp,upper}$	0.2		d
Lower threshold of water stress for canopy expansion	$p_{exp,lower}$	0.6		d
Shape factor for canopy expansion		3		d
Senescence stress coefficient	p_{sen}	0.55		d
Shape factor for senescence		3		d
Phenology				
GDD from sowing to emergence/recovery		90	degree-day	r
GDD from sowing to maximum rooting depth		756	degree-day	r
GDD from sowing to flowering		810	degree-day	a
GDD from sowing to start of senescence		925	degree-day	r
GDD from sowing to maturity		1350	degree-day	r
Length building up of HI		150	degree-day	a
Base temperature	T_{base}	2	$\circ$ C	
Cut-off temperature	T_{upper}	28	$\circ$ C	AAF
Harvest				
Reference Harvest Index	HI_0	0.52		a
Reference atmospheric CO_2 concentration (2006)		369.41	ppm	

*d: default, AAF: Alberta Agriculture and Forestry (Alberta Agriculture and Forestry (AAF), 2016, 2008, n.d.), c: calculated, a: assumed, r: Langhorn (2015)

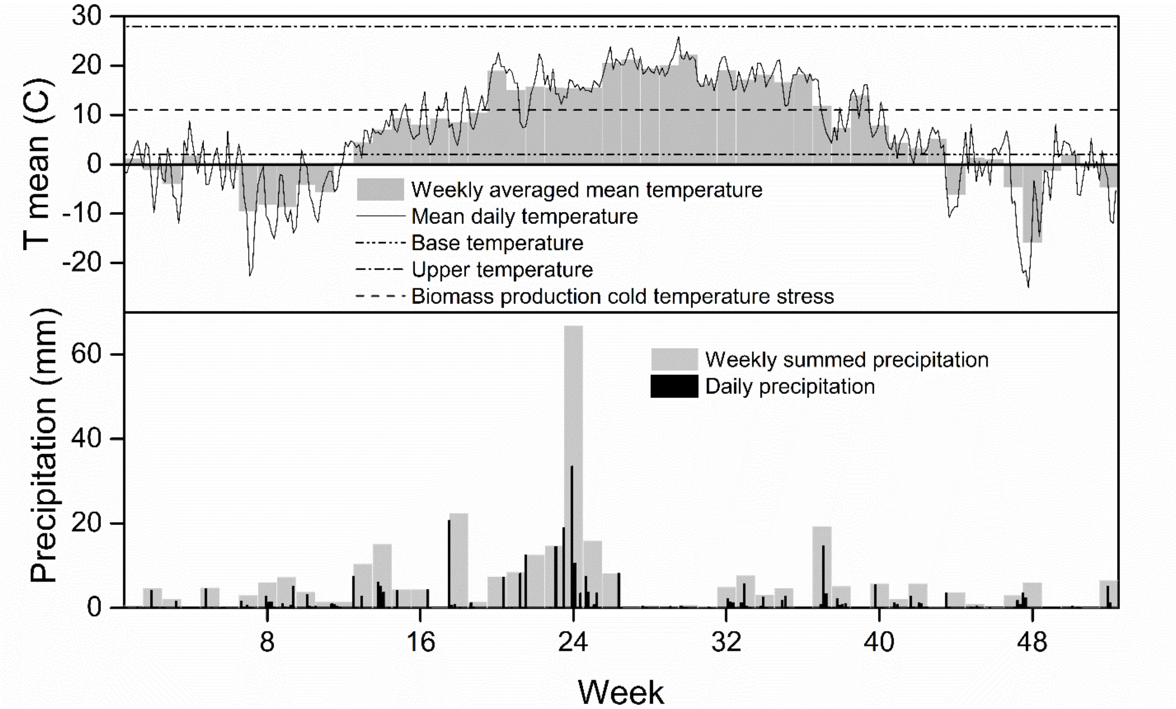

Figure 2.1. Sample input to the models: Weekly-averaged mean temperature and precipitation input data for CropSD versus the daily mean temperature and precipitation input data for AquaCrop. Values are shown for 2006, which was chosen arbitrarily as an example, for Enchant, Alberta, Canada. Mean temperatures are plotted against threshold base and upper temperatures for barley. Base temperature is the temperature below which crop development does not progress. Upper temperature threshold is the temperature at which the plant no longer develops with an increase in air temperature (Hsiao et al., 2009).

2.3.3 Evaluation criteria

Daily simulation results from AquaCrop based on daily weather input data are used as the reference mode for comparison with results from CropSD for daily, semi-weekly, and weekly time steps with weekly input data. Simulations were compared through statistical measures and graphical results. Using smaller numbers of indicators for assessing model performance can misrepresent average errors and deviations (Chai and Draxler, 2014; Tedeschi, 2006), and thus a combination of metrics were used. The following statistical indices and errors were computed to compare the crop biomass and yield: coefficient of determination (R^2); root mean square error of prediction (RMSE) and its normalized version (NRMSE); mean absolute error (MAE); mean bias error (MBE); and Willmott agreement index (d) (Willmott, 1982). These evaluation procedures have been applied widely to assess crop growth model performance (Abi Saab et al., 2015; Araya et al., 2010; Hsiao et al., 2009; Hussein et al., 2011; Stricevic et al., 2011; Todorovic et al., 2009). Absolute error measures (such as RMSE or MAE) are given more weight for performance assessments, as they provide quantitative estimates of the deviation of the modeled variables from anticipated values, and present the error in the same units as the variable (Bellocchi et al., 2010; Legates and McCabe Jr., 2005; Moriasi et al., 2007).

The coefficient of determination (R^2) is the magnitude of variance explained by the model compared with the total observed variance. R^2 ranges from 0 to 1. A value closer to 1 shows a better agreement. The average differences between the reproduced model simulation results of biomass and crop yield and AquaCrop results were described by the root mean square error (RMSE) and the normalized root mean square error (NRMSE) as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \tag{2.1}$$

$$\mathrm{NRMSE} = \frac{100}{\overline{M}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \tag{2.2}$$

where n is the number of pairs of data, and S_i, M_i, and $\overline{M}$ are the CropSD simulation results, AquaCrop results, and mean AquaCrop values, respectively.

In addition, the Index of Agreement (d) was calculated according to Willmott (1982) as follows:

$$d = 1 - \frac{\sum_{i=1}^{n} (S_i - M_i)^2}{\sum_{i=1}^{n} (|S_i - \bar{M}_i| + |M_i - \bar{M}_i|)^2} \tag{2.3}$$

The value d represents the ratio between the mean square error and the potential error and ranges from 0 to 1.0, with a value of 1.0 indicating excellent agreement.

The mean bias error (MBE) (Fox, 1981; Willmott, 1982) was also used to indicate the under/over estimations by the reproduced model as follows:

$$\mathrm{MBE} = \frac{1}{n} \sum_{i=1}^{n} (S_i - M_i) \tag{2.4}$$

Similarly, the mean absolute error (MAE) is calculated as follows:

$$\mathrm{MAE} = \frac{1}{n} \sum_{i=1}^{n} |S_i - M_i| \tag{2.5}$$

Finally, the Modeling Efficiency (ME) was used to evaluate the overall model performance. ME determines the relative magnitude of the residual variance of CropSD compared to the AquaCrop simulation variance (Nash and Sutcliffe, 1970). ME ranges from $-\infty$ to 1.0, and the closer the result is to unity, the more robust the model is. ME is computed as:

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M}_i)^2} \tag{2.6}$$

Three model variables were also evaluated visually by plotting CropSD and AquaCrop outputs, i.e., soil water content, crop canopy cover, and cumulative actual evapotranspiration. This choice of variables incorporates key aspects of model performance related to the soil water balance, the crop growth mechanism, and the connection of the two components by considering both the actual evaporation from the soil and the actual transpiration by the crop canopy, which sum to the actual evapotranspiration.

2.4 Results

Results in this section are presented for irrigated barley biomass and crop yields at Enchant, Alberta, Canada. The results for maize and potato biomass and yield for the three simulation time steps in the two other locations are provided in sections S2 and S3, respectively, of the Supplementary Material, along with descriptions of the associated input data and crop parameters. Values for the coefficient of determination (R^2), the root mean square error (RMSE), the normalized root mean square error (NRMSE), the index of agreement (d), and the mean absolute error (MAE) for daily, semi-weekly, and weekly simulations for each simulation time step are shown in Figure 2.2 for the biomass and crop yield. Soil water content, green canopy cover, and actual evapotranspiration for four sample site-years for each simulation time step are presented in Figures 2.3, 2.4, and 2.5 to illustrate the model's behavior graphically.

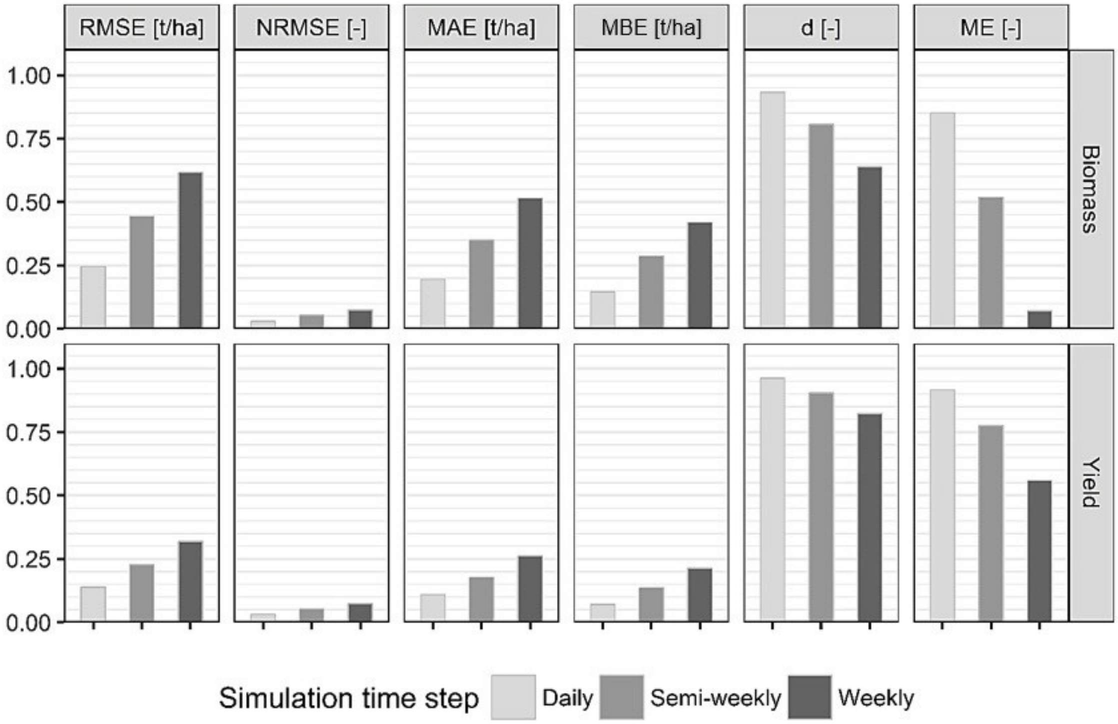

Figure 2.2. Crop biomass and crop yield statistics for CropSD versus AquaCrop simulations, based on ten growing seasons and four different irrigation treatments for Enchant, Alberta. Statistics include the root mean square error (RMSE), normalized root mean square error (NRMSE), mean absolute error (MAE), mean bias error (MBE), index of agreement (d), and model efficiency (ME). Higher numbers for d and ME indicate better model performance while lower numbers for RMSE, NRMSE, MAE, and MBE are preferred.

Regression analyses for aboveground biomass and crop yield are presented in Figure 2.3 and Figure 2.4, respectively. Daily simulations from the CropSD model with weekly weather data inputs showed high R^2 values for both biomass and yield simulations, suggesting a high degree of reliability for aggregated weekly input climate data. Further, daily simulations had the lowest NRMSE with a maximum value of 5% and for both biomass and yield. Semi-weekly simulations, similarly, showed good statistics with a maximum NRMSE of 7% for biomass and 9% for crop yield, while the weekly time step simulations had the lowest model performance and less agreement with AquaCrop, with a maximum NRMSE of 10%, and R^2 as low as 0.3 for both the biomass and the final yield. Additionally, deviations from the 1:1 straight line for the semi-weekly and weekly simulations were slightly higher than for the daily simulations, and this deviation increased with increasing simulation time steps.

The coarser time step simulations exhibit slight overestimations of both the biomass and the crop yield for the three simulation time steps. For daily simulations, the maximum mean bias error (MBE) was 0.237 t ha^{-1} and 0.135 t ha^{-1} for biomass and yield, respectively, while the maximum MBE for semi-weekly simulations was 0.408 t ha^{-1} for biomass and 0.272 t ha^{-1} for crop yield. The highest MBE was 0.453 t ha^{-1} for biomass and 0.359 t ha^{-1} for crop yield for the weekly simulations.

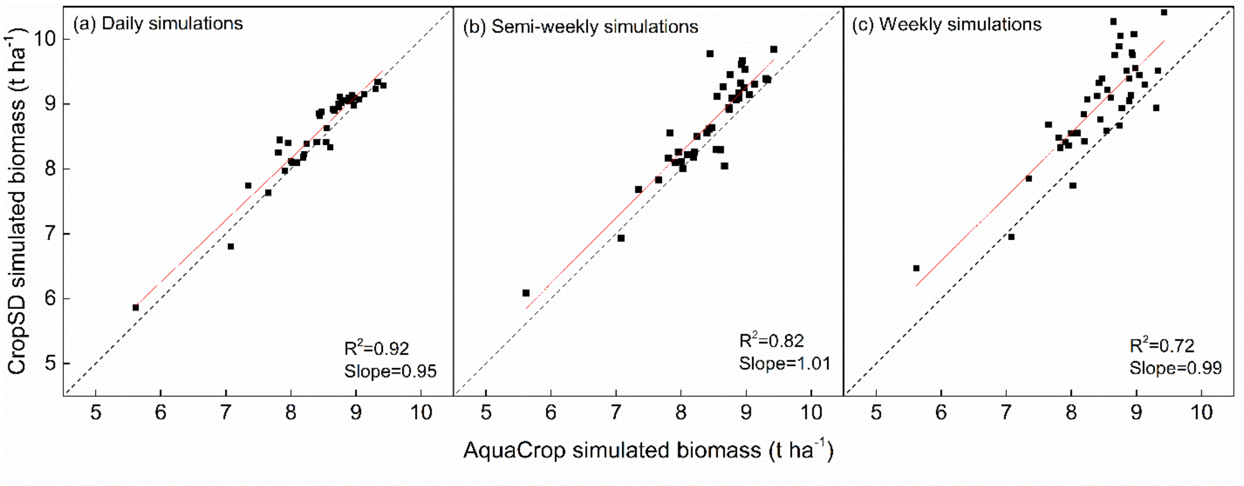

Figure 2.3. Aboveground biomass estimated by CropSD *versus* AquaCrop estimates for barley for the different irrigation treatments over ten growing seasons. The Coefficient of Determination (R^2) and the slope are also shown. Figures. a, b, and c represent the daily, semi-weekly, and weekly simulations respectively for Enchant, Alberta.

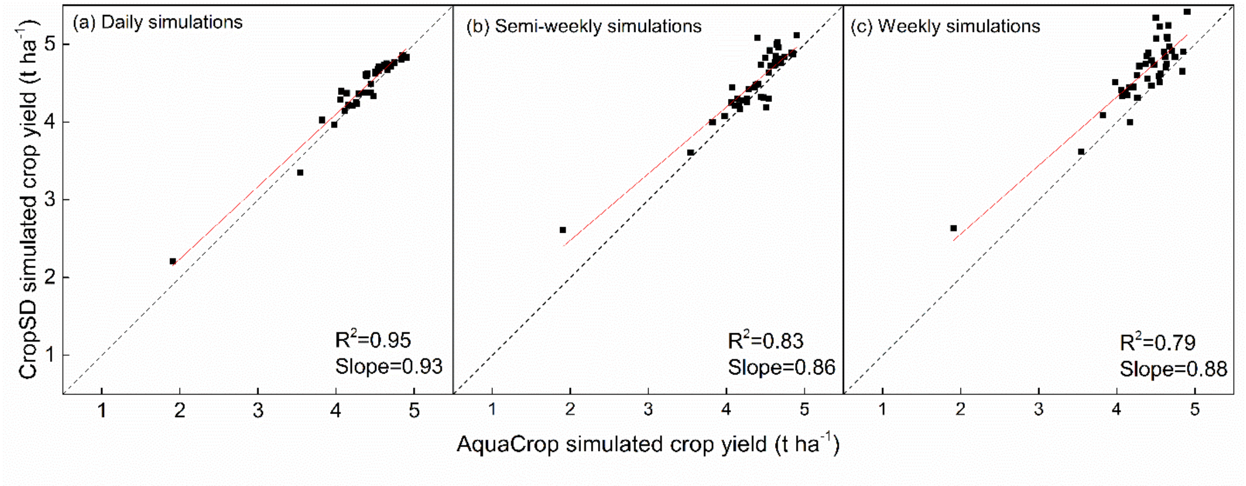

Figure 2.4. Crop yields estimated by CropSD *versus* AquaCrop estimates for barley for the different irrigation treatments over ten growing seasons. The Coefficient of Determination (R^2) and the slope are also shown. Figures. a, b, and c represents the daily, semi-weekly, and weekly simulations respectively for Enchant, Alberta.

Figure 2.5 provides sample graphical plots that compare daily CropSD and AquaCrop simulation results for soil water content, crop canopy cover, and cumulative actual evapotranspiration variables for the growing seasons of 2010, 2011, 2012, and 2013 with the T20, T40, T60, and T100 irrigation treatments respectively at Enchant, Alberta. Similarly, Figures. 6 and 7 compare the semi-weekly and weekly CropSD simulations, respectively, with AquaCrop results for the same growing seasons and irrigation treatments.

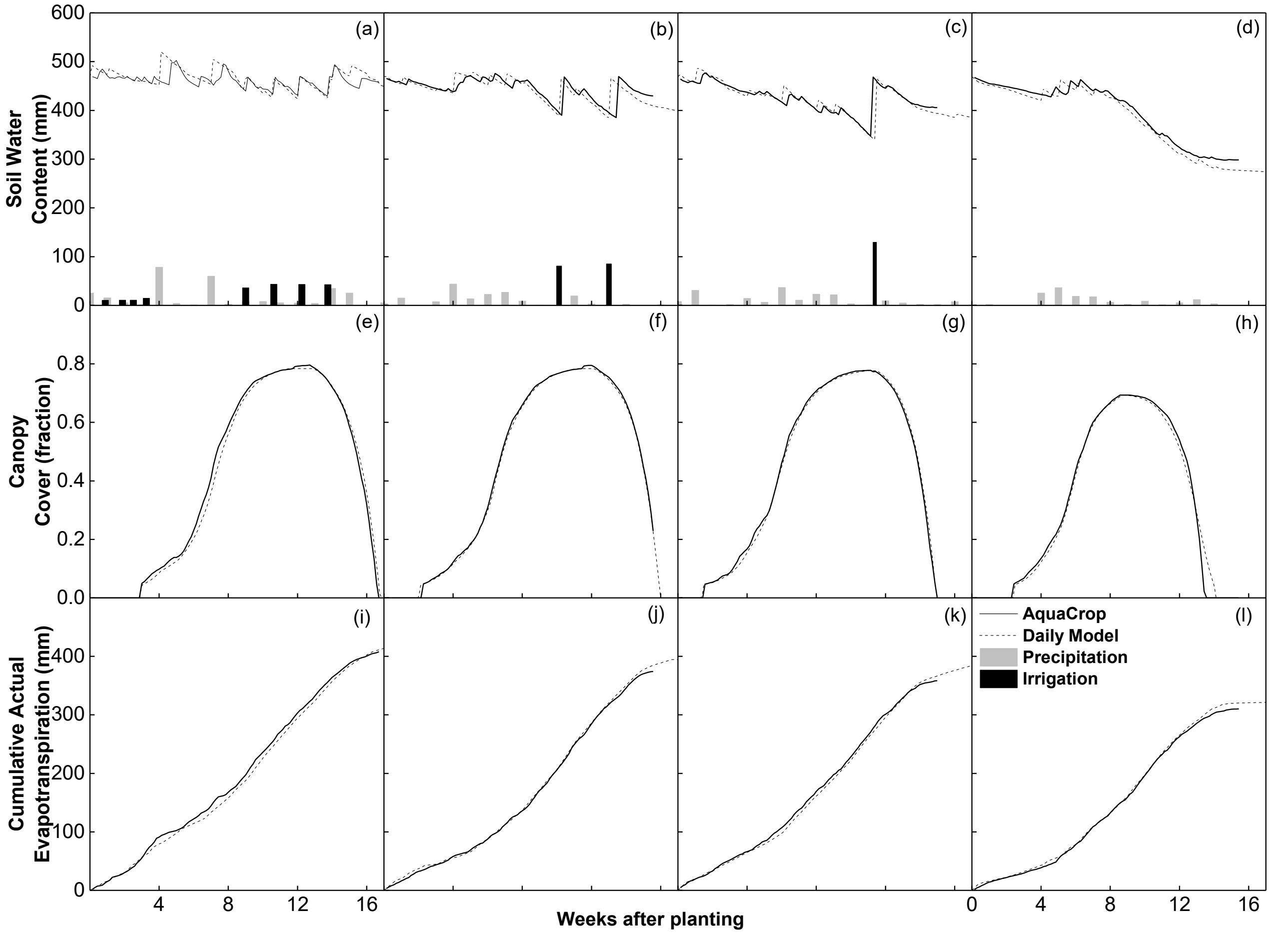

Figure 2.5. CropSD daily time step model. Simulated soil water content, crop canopy cover, and cumulative actual evapotranspiration are shown versus simulations from FAO's AquaCrop for the four growing seasons of 2010 (a, e, i), 2011 (b, f, j), 2012 (c, g, k), and 2013 (d, h, l) under four irrigation treatments (T20, T40, T60, and T100) for barley. Precipitation and irrigation events produced by CropSD are also plotted within the soil water content graphs.

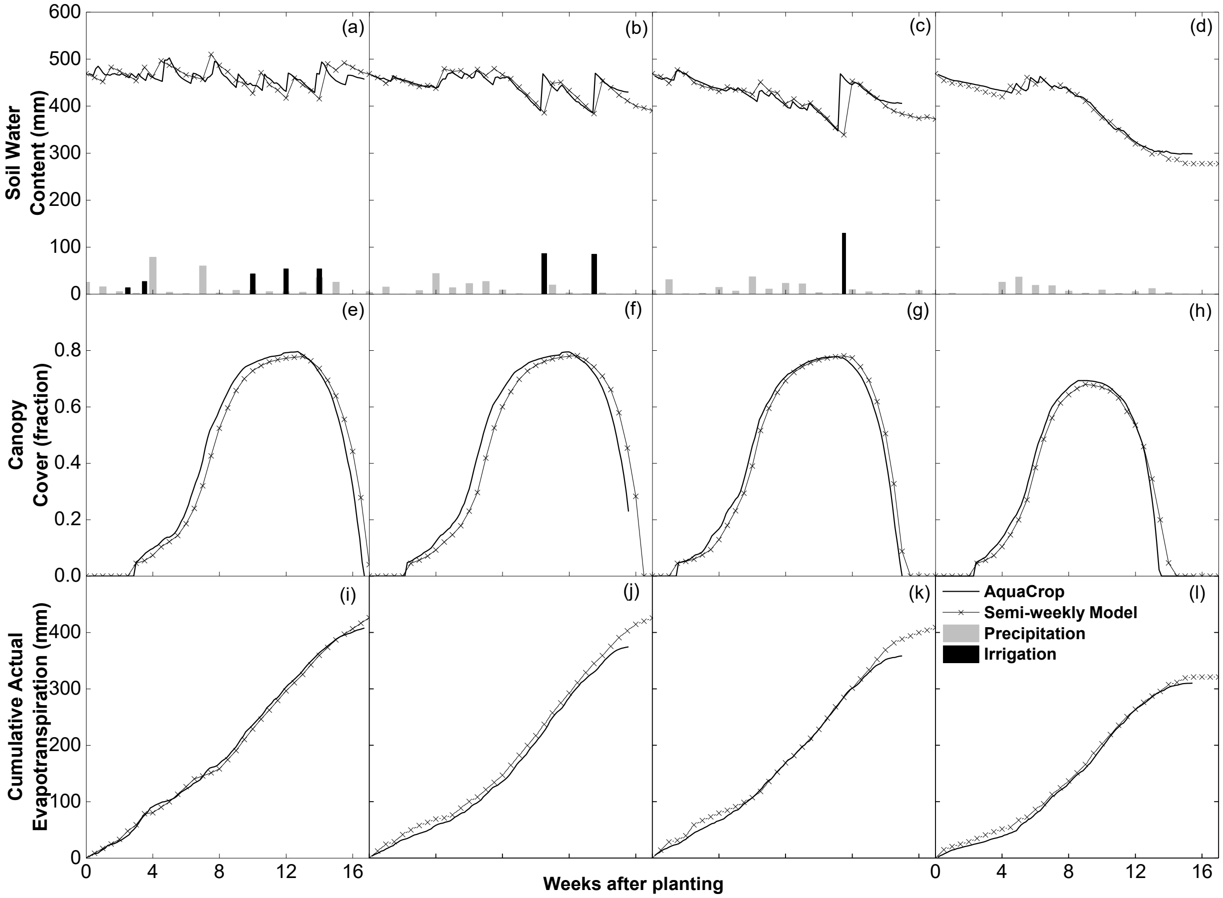

Figure 2.6. CropSD semi-weekly time step model. Simulated soil water content, crop canopy cover, and cumulative actual evapotranspiration are shown *versus* simulations from FAO's AquaCrop for the four growing seasons of 2010 (a, e, i), 2011 (b, f, j), 2012 (c, g, k), and 2013 (d, h, l) under four irrigation treatments (T20, T40, T60, and T100) for barley. Precipitation and irrigation events produced by CropSD are also plotted within the soil water content graphs.

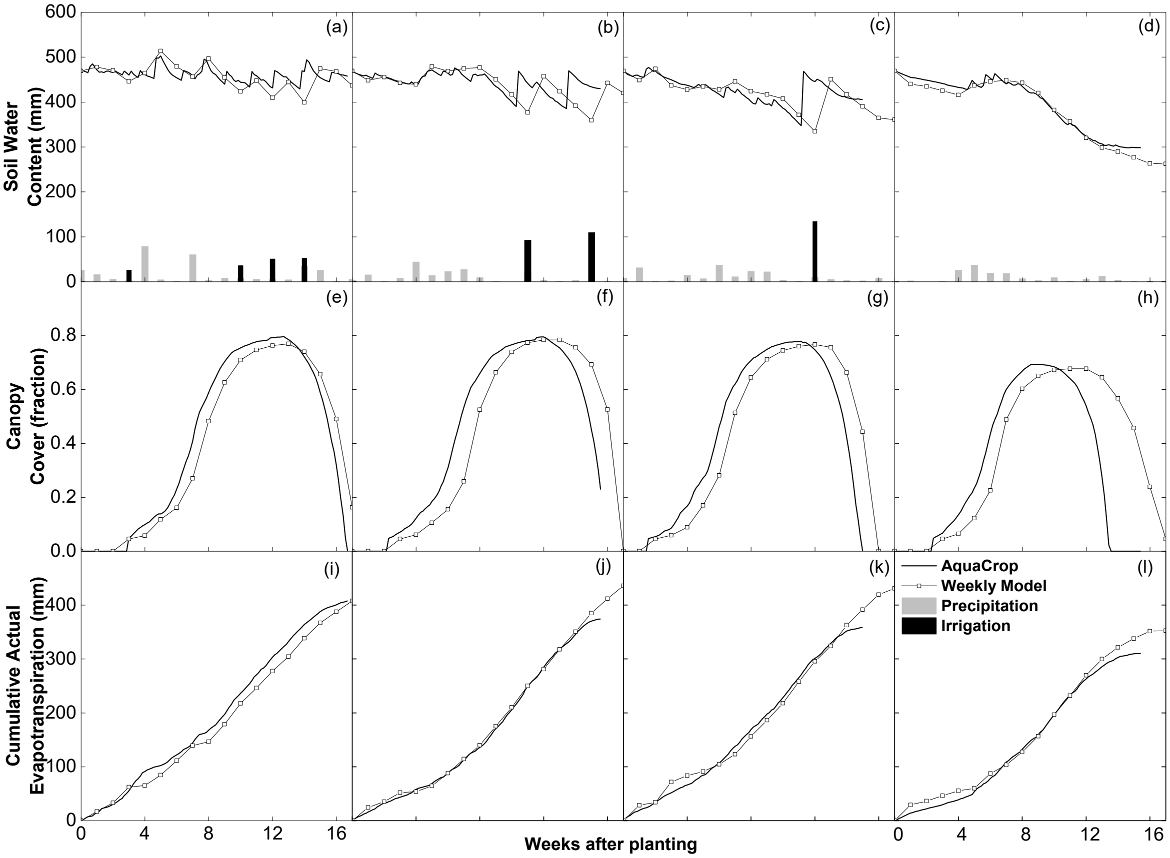

Figure 2.7. CropSD weekly time step model. Simulated soil water content, crop canopy cover, and cumulative actual evapotranspiration are shown *versus* simulations from FAO's AquaCrop for the four growing seasons of 2010 (a, e, i), 2011 (b, f, j), 2012 (c, g, k), and 2013 (d, h, l) under four irrigation treatments (T20, T40, T60, and T100) for barley. Precipitation and irrigation events produced by CropSD are also plotted within the soil water content graphs.

The effect of aggregating daily precipitation into single weekly input values for CropSD is visible in Figures 2.5(a), 2.6(a), and 2.7(a) for the daily, semi-weekly, and weekly simulations, respectively, for rainfall events at weeks four and eight after planting. In theory, the aggregation of input data could have two possible consequences for the soil water balance: 1) for dry soils, a single, relatively large weekly precipitation event could produce higher soil moisture as compared with smaller daily precipitation events, or 2) for wet soils in the receiving top layer, larger runoff events could cause less water infiltration and relatively lower soil moisture. Because no adjustment to the curve number of the topsoil layer of the soil profile was performed, the model behavior corresponded to the first case and tended to calculate slightly higher moisture for the soil profile than crop models driven with daily input, regardless of the time step used.

Longer time steps also affected the simulation of irrigation timing and soil water depletion. Specifically, irrigation applications that fell between two calculation time steps in the semi-weekly and weekly model versions permitted water depletion to exceed the user-set allowable value, because the "trigger to irrigate" (soil water depletion) was delayed until the start of the next calculation step. Therefore, the number of irrigation events was reduced, but the application depths increased to account for the longer delay in applying irrigation, as shown in Table 2.4. The result was a higher depletion ratio and less available soil moisture for the crop. This effect was particularly apparent at low allowable depletion ratios (as in T20), where small and more frequent irrigation events were required in the AquaCrop and daily time step CropSD models early in the growing season (Figure 2.5a), because the short roots depleted the required moisture only from the top soil layers and triggered more irrigation events in a short period of time. For example, daily time step simulations resulted in eight irrigation events for T20 (Figure 2.5a) during the growing season, which agreed with AquaCrop simulations, while five and four irrigation applications for semi-weekly (Figure 2.6a) and weekly (Figure 2.7a) time step simulations, respectively, were generated.

Table 2.4. Irrigation events characteristics for T20, T40, and T60 for Enchant study location for 2010, 2011, and 2012, respectively.

Model	Number of irrigation events	Minimum irrigation depth (mm)	Maximum irrigation depth (mm)	Seasonal irrigation depth (mm)
			T20	
AquaCrop	8	14	45	238
CropSD				
Daily	8	11	44	228
Semi-weekly	5	14	54	192
Weekly	4	26	55	165
			T40	
AquaCrop	2	84	87	171
CropSD				
Daily	2	81	86	166
Semi-weekly	2	85	86	171
Weekly	2	93	110	202
			T60	
AquaCrop	1	-	-	128
CropSD				
Daily	1	-	-	130
Semi-weekly	1	-	-	130
Weekly	1	-	-	134

CropSD with weekly data inputs simulated the canopy cover (CC) development throughout the growing season identically to AquaCrop under the four irrigation treatments, as presented in Figure 2.5(e, f, g, and h). Likewise, the semi-weekly CropSD simulations were almost identical to the CC development from AquaCrop; however, a slight delay in the logistic curve of the canopy growth (Geerts et al., 2009; Steduto et al., 2009) before reaching its maximum value resulted in an overall CC development delay over the growing season – see Figure 2.6(e, f, g, and h). This CC development delay increased with increasing simulation time step, as shown by comparing the weekly time step results in Figure 2.7(e, f, g, and h) with the daily and semi-weekly simulations. Moreover, weekly simulations occasionally resulted in a larger incremental exponential growth during canopy development. Specifically, the weekly time step CropSD simulations occasionally overshot the growth logistic curve and hence the maximum canopy cover was reached earlier in the season; therefore, the model overestimated transpiration, crop biomass, and crop yield. In other cases, as shown in Figure 2.7(h), crop senescence was triggered later in the season, resulting in a larger accumulation of biomass and thus overestimated crop yields.

Seasonal actual evapotranspiration (ET) tended to be overestimated regardless of the simulation time step, a result particularly apparent towards the end of the growing season, and likely attributable to the aggregation of the weather input data. Overestimation increased consistently with increasing simulation time step, as shown by comparing Figure 2.5(i, j, k, and l), Figure 2.6(i, j, k, and l), and Figure 2.7(i, j, k, and l).

Figure 2.8 uses regression 1:1 plot to compare the total results for daily, semi-weekly, and weekly time steps with aggregated weather input data against AquaCrop for biomass and crop yield, respectively. The figures include results for all the irrigation scenarios over ten growing seasons (2006 to 2015) at both Enchant and Fincastle, Alberta; therefore, each time step-based data set has a total of 80 data points (10 years x 4 treatments x 2 locations) for each of biomass and yield at both locations. The figures show that CropSD reproduced AquaCrop values well for daily and semi-weekly time steps with weekly aggregated climate input data. Specifically, NRMSE values for biomass and crop yield, respectively, were 3% and 5%, and 3% and 6%, for daily and semi-weekly time steps. Results were less promising for the weekly simulations – recall particularly the low ME value for biomass in Figure 2.2, indicating that the weekly time step model may not be used with confidence. Further, deviations for lower biomass and crop yield estimates (values closer to the origin) were found to be higher than for high-yielding conditions. These deviations also increased with increasing simulation time step length.

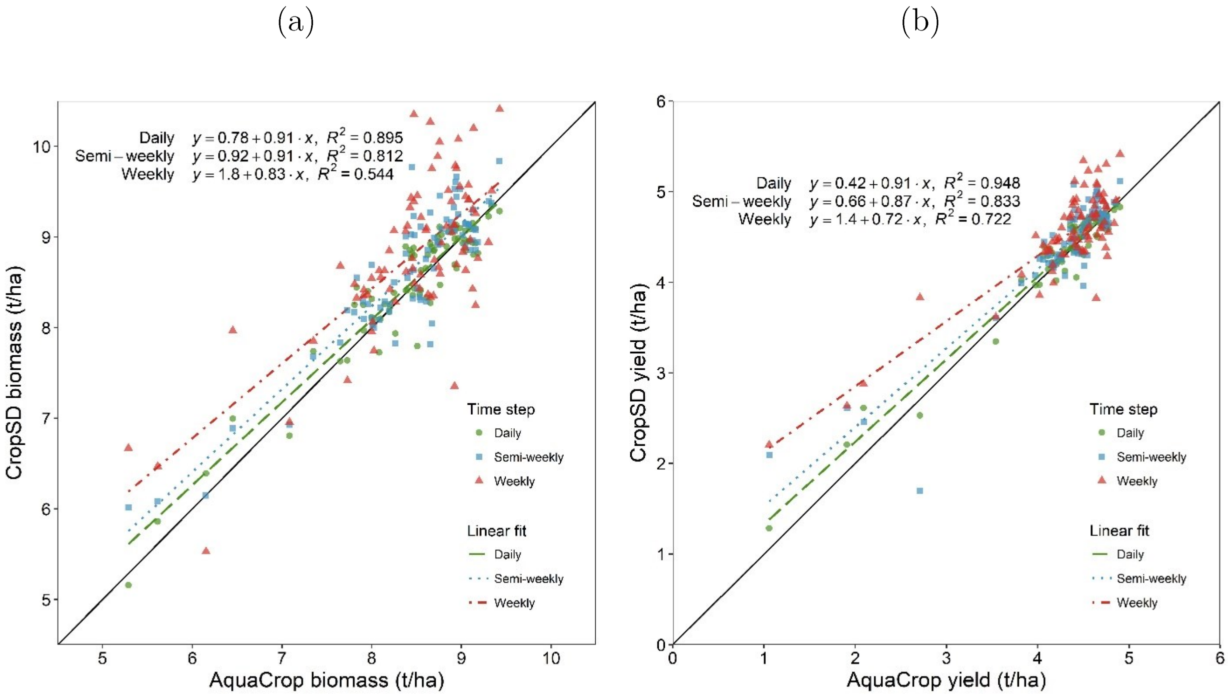

Figure 2.8. Daily, semi-weekly, and weekly time-step results for CropSD versus AquaCrop in simulating (a) final aboveground biomass and the (b) crop yield for the two study locations of Enchant and Fincastle. Each of the three datasets has 80 estimated data points derived from simulating two locations for barley crop over ten growing seasons using four irrigation treatments.

2.5 Discussion

2.5.1 Implications of simulation time steps for crop biomass and yield estimates

When both models were run at a daily time step, biomass production and crop yield in AquaCrop and CropSD differed slightly for two reasons. First, climate data for CropSD were input as weekly averages for the temperature, relative humidity, and wind speed, and the total weekly precipitation was applied at the beginning of the week. Second, CropSD operates with a base time unit of one week, and uses the Euler method to solve the differential equations numerically, which changes time steps according to a geometric progression with a common ratio of one-half (Lehn et al., 2002); therefore, the model ran at a time step of one-eighth of a week rather than one-seventh, introducing a slight discrepancy in values.

In the coarser semi-weekly and weekly time step simulations, delayed canopy growth in the early stages of crop development resulted, in most cases, in a lag period of up to half a week for the semi-weekly simulation and up to a week in the weekly time step simulation. The fact that this effect was more pronounced with longer simulation time steps adds uncertainty to the use of weekly time steps. The delay may occur for one or both of the following reasons: (i) higher soil water depletion was permitted than the specified irrigation threshold because of the coarser time step, since the irrigation threshold was reached between two computation steps, or (ii) computational errors occurred that were associated with the Euler integration method. Integration error is proportional to the square of the time step; therefore, coarser integration step-sizes correspond to larger errors. The first reason was more evident in weekly simulations, where irrigation was simulated as taking place later in the season – see Figure 2.7(a, b, and c). Clearly, although weekly simulations may have advantages in terms of run time, the results are not promising for biomass or crop yield estimations where accuracy is critical. Weekly time step results consistently showed large deviations from AquaCrop results in terms of soil water moisture, canopy cover, and seasonal ET, because of changes in simulated variables that occurred too quickly for the weekly time step to capture accurately.

2.5.2 Implications of simulation time steps for soil water moisture, canopy cover, and seasonal evapotranspiration

Soil layers in CropSD tended to retain moisture above field capacity longer than AquaCrop, because of a modification in the calculation of infiltration processes at longer time steps. The effect was particularly evident for larger precipitation events (which were aggregated to weekly input values) with semi-weekly and weekly time steps. In most cases, the coarse simulation time steps were longer than the time water would require to infiltrate from one layer to another in coarse soil textures with higher hydraulic conductivities. Therefore, the drainage and distribution component of the model was modified (see Table S2) in both the semi-weekly and weekly simulations settings, such that CropSD bypassed calculation of the drainage and redistribution functions and assumed any water above field capacity in the soil layers drained instantly after a heavy rain or an irrigation event. That approach maintains field capacity as the maximum soil water content, because it approximates the final state (post soil-water redistribution) of the soil moisture after a wetting event.

The canopy is a central component of the model because it drives the actual transpiration, which in turn determines the biomass production and thus the crop yield (Raes et al., 2009; Steduto et al., 2009). AquaCrop simulates canopy cover development in terms of GDD increments, starting from transplanting or sowing to the final harvest. A coarser simulation time step causes larger incremental increases in GDD accumulation. In some cases, the GDD accumulation over one time step (particularly for the weekly time step) was large enough for the exponential growth component of the logistic curve to overshoot and thus exceed the maximum canopy cover; where this occurred, the model bypassed the decay component of the logistic curve. Consequently, the canopy cover was represented unrealistically, as seen in Figure 2.7h, where the development curve was composed only of exponential growth and was then capped at the maximum crop canopy cover. In general, the simulation time step should be smaller than the shortest period over which a change in a model variable is likely to occur. Otherwise, the model behavior may differ significantly from what would occur with a smaller time step, as demonstrated by the soil water content in Figure 2.7(a, b, and c).

Systematic overestimation was observed for the seasonal ET in CropSD, as compared with AquaCrop. This overestimation, and its increasing magnitude with coarser time steps, was attributed to the delayed canopy development by the model. The delay resulted in larger transpiration rates towards the end of the season, where the canopy cover senescence was triggered later in the season than in reality, such that more transpiration took place and increased the seasonal ET.

2.5.3 Implications of aggregated weather input data for model performance

Lack of day-to-day variability in maximum and minimum temperatures – and the corresponding absence of extreme temperatures – resulted in higher estimated aboveground biomass and crop yields. This result was in line with expectations and the literature (Nonhebel, 1994; Soltani et al., 2004), and its occurrence is more likely in regions/conditions of high temperature variability. Specifically, in our study locations, both cold and heat stresses were reduced or eliminated by the weekly averaging of CropSD input (recall Figure 2.1, above); therefore, overestimations in biomass production and crop yield are more likely caused by these omitted cold/hot air stresses than by differences in the accumulated thermal heat units. This conclusion matches that of van Bussel et al. (2011), whose overestimation of simulated biomass was driven by a lack of weather variability with interpolated daily temperature and radiation data. That resulted in higher photosynthetic rates since averaged temperatures are more often at or near optimum values for growth. For instance, heat stresses are known to affect crop production strongly (Hatfield and Prueger, 2015), and their damaging effects can occur after exposure to high temperatures of only three days for barley (Savin and Nicolas, 1996), and only one day for wheat (Saini and Aspinall, 1982). Likewise, cold stresses decrease root hydraulic conductance, which reduces or ceases their growth and ultimately reduces crop production (Thakur et al., 2010) after exposure to cold temperatures for as little as one day (Ercoli et al., 2004). Such damages due to extreme weather events such as heat stresses or cold stresses were not within the scope of our analysis.

Finally, Lorite et al. (2005) considered the effects of temporal aggregation on irrigation requirements using the statistical crop production function of Doorenbos and Kassam (1979), and showed little effect of temporal aggregation on seasonal irrigation requirements up to monthly time steps. However, while Lorite et al. (2005) found decreased irrigation requirements with larger time steps, our analysis showed that longer simulation time steps caused both the number of irrigation events and the seasonal-total irrigation depth to decrease only for low allowable depletion ratios (T20) – see Table 2.4. This is due to irrigation events occurring at a shorter interval than the simulation time step. In contrast, the total number of irrigation events and seasonal irrigation depth for both T40 and T60 were comparable to those by AquaCrop, because the intervals between irrigation events were longer than the semi-weekly and weekly time step, and thus the model was able to accurately capture the events.

2.6 Conclusions

For high level policy planning and strategic decisions under climate change, integrating agricultural systems into wider socioeconomic, environmental, or hydrologic applications requires the accurate simulation of agricultural production through process-based crop models. In such applications, the key model outputs include, for example, crop biomass and yield, and water demand, rather than the simulation of the crop phenological development. We hypothesized that process-based crop models can operate accurately under coarser-than-daily simulations and with aggregated weather input data, and that such an approach would provide a useful compromise between accuracy, model input and integration requirements, data collection efforts and model execution time.

We tested the hypotheses with a revised version of a water-driven crop model, AquaCrop, designed to operate with a coarser time step and weekly input data. This model, called CropSD, then provided insights on the behavior of a process-based crop model in simulating crop yield and water requirements under such conditions. We found that aggregation of weather data resulted in a slight overestimation of both the biomass and yield. Longer time steps amplified the impacts of weather input data aggregation, and overestimation became more pronounced with increases in the simulation time step. Both daily and semi-weekly time steps simulations agreed closely for crop growth and production, and soil moisture simulations. As compared with the AquaCrop results, weekly time step CropSD simulations consistently showed the highest deviations and the lowest performance for all model variables: crop biomass and yield, soil water moisture, canopy cover, and seasonal ET.

Our results showed that 1) water-driven process-based approaches to crop modeling can operate accurately at coarser simulation time steps than daily, and 2) a semi-weekly time step may provide a promising alternative in conjunction with coarser temporal resolution weather input data up to weekly. This combination yielded satisfactory results in simulating the end of season crop yields and water demand estimations. This has important implications for coupling crop models for integrated assessments with other socioeconomic, environmental, or hydrologic models, and therefore provides guidance for modelers involved in interdisciplinary integrated agricultural and water applications under future climate scenarios including policy assessment, food security, and resource use and efficiency. Note that more detailed models than AquaCrop exist, some of which are sufficiently complex to render them unsuitable for integration with other models for integrated assessment purposes (e.g., policy and strategic planning applications). Additionally, this analysis serves several of the desirable features Antle et al. (2017) identified for producing the second generation of agricultural systems models, or "NextGen" models (Antle et al., 2017a; Capalbo et al., 2017; Janssen et al., 2017; Jones et al., 2017b), particularly the temporal scaling features for crop models and the systems approach.

Finally, the results of this analysis are influenced by the features of AquaCrop model and its mathematical relationships in defining crop canopy cover, transpiration and biomass accumulation. To generalize the hypothesis that coarser simulation time steps for process-based crop models are suitable for incorporation into integrated assessments, further investigation of the characteristics of the specific crop model to be used may prove worthwhile. In particular, given the results for the weekly time step simulations, a process-based model may be more detailed than necessary and functional approaches with simplified processes could be better suited.

Connecting Text To Chapter 3

This chapter describes the development of a list of water policy alternatives to address water scarcity and to cope with water shortages in a river basin. A number of the policy alternatives described here will be assessed in Chapter 4 as adaptation measures to climate change and expansion of Alberta's irrigation sector.

Chapter 3. Water policies for agricultural, municipal, and industrial sectors: A list for modelers and policymakers

3.1 Introduction

Water policies are vital tools that can address water scarcity in a river basin. They are always thought of to exploit alternative sources of water or to conserve water and reduce demands. Water scarcity relates to either water is physically scare thus a supply problem or available but should be managed differently and thus a demand problem (Rijsberman, 2006). It can be attributed to uneven spatial and temporal distributions of freshwater supplies, population growth, and socioeconomic development. Atop of that, with the negative impacts induced by climate change on water resources (Gizaw and Gan, 2016; Mishra et al., 2017; Siam and Eltahir, 2017; Steele et al., 2018; Tariku and Gan, 2018), it is expected that water scarcity will persist, and even worsen without the careful selection and implementation of water adaptation strategies and policy interventions at a river basin – which is the fundamental unit for water management (Barrow, 1998; Chenoweth, 1999; Houdret et al., 2014; Molle, 2009; Smith et al., 2014).

Various concepts and frameworks have been developed in the literature to understand water as a resource, on the one hand, and its integration with other resources, on the other, and to improve its management into the future. Concepts include Integrated Water Resources Management (IWRM) (GWP, 2000; Rahaman and Varis, 2005; Varis et al., 2014), and the nexus across water, food, and energy (Allan et al., 2015; Bazilian et al., 2011). Each has a different level of maturity across both the academic and the legislative domains resulting in various definitions and a wide range of interpretations. They are typically defined broadly and aim to integrate water availability, use and quality, and the sustainability of human and ecosystem functions while maximizing social welfare and environmental quality at a river basin. Practical applications apply narrower definitions that are intended to aid precise identification and assessment of specific concerns, and that are often suited to computer modeling (Cook and Bakker, 2012). Such concepts share a focus on identification and application of appropriate "interventions" (termed, alternatively, policy instruments/measures, adaptation or mitigation strategies, or management decisions). Yet, a comprehensive catalogue of such "interventions" at a river basin scale is lacking, despite its potential utility for implementing IWRM (Basco-Carrera et al., 2017b), water-food-energy nexus (Abdelkader et al., 2018; Uen et al., 2018), and additionally, Integrated Assessment and Modeling in water resources (IAM) (Hamilton et al., 2015), or water governance (Pahl-Wostl et al., 2010; Sampson et al., 2016; Xu et al., 2018).

Therefore, this paper is motivated by two main objectives. First, catalogue an extensive list of water policies at the river basin considering the common divisions of water demands estimations and management, namely the agricultural, municipal, and industrial water sectors. Second, present examples of modeling exercises undertaken to quantify each of the policy alternatives. The paper provides a list of policies that have received notice over the past two decades by policymakers, water researchers, and water resources modelers. Policies listed here aim to cope with water shortage resulting from population growth and associated socioeconomic development, short- and long-term droughts, climate change, competition between different water sectors, or so much as in the paradigm of Integrated Water Resource Management (IWRM) application, in which multiple aspects of water supply and demand are considered. Current policy modeling practices are also briefly discussed for each of the three water sectors identified. The challenges a modeler may encounter in an attempt to devise a suit modeling tool to quantify policy effects are examined. In this paper we adopt the term "policy" as an inclusive term for, and interchangeable with, "adaptation", "intervention", and "management option".

In total, 237 studies were analyzed. The review did not aim to cover every relevant study, but instead to compile an extensive list of water policy tools and a representative set of modeling examples that address water scarcity using these tools. This catalogue of policy alternatives is intended to provide water management researchers and modelers, water managers, and policymakers with a detailed set of options for managing water scarcity in the three key water demand sectors. For modelers, the catalogue provides a comprehensive list of policy measures to address water scarcity in a river basin scale, as well as specific examples of studies that have attempted to model them.

3.2 Defining water policy: an overview of choice and modeling of water policies

What is water policy? There is no universal definition of the word "policy" in the water resources community. The term can be defined differently whether it is treated quantitatively in a modeling exercise or in an executive/legislative context by decision makers. Modelers refer to "policy" as a set of changes in appropriate model parameters as policy levers to analyze and understand the effects of certain strategies, or management options in a given system (model) (Qi and Chang, 2011; Simonovic and Fahmy, 1999; Stave, 2003; Wang and Davies, 2018). These parameters are often in the form of initial values, constants, switches (to enable or disable a certain model feature), or exogenous variables (Davies and Simonovic, 2011; Inam et al., 2017a; Therond et al., 2009). It is also used interchangeably with "scenario" in modeling studies. While decision makers use the term to describe a plan or a set of actions to reach a specific future goal.

Choosing the most effective policy alternatives for alleviating water shortages or increasing water security is not straightforward. Policymakers typically make decisions based on past experiences and the need to meet specific goals. Where their approach is quantitative, they may define criteria and assign weights to each for the evaluation of different policy instruments – a subjective approach, since each policymaker ranks the criteria differently (Mukheibir, 2008). Where the public is involved, Hamilton et al. (2015, p. 217) explain, "*The challenge for managing wicked environmental problems is that stakeholders have different, and many times conflicting, views about the issue and how it may be managed*". The result of these disagreements and uncertainties is that "*…improving our governance policies and procedures takes even more time than obtaining the funding needed to improve our infrastructure systems*" (Cosgrove and Loucks, 2015, p.4836). Perhaps the reason is the lack of understanding and confidence in a policy outcome. This is where models and modelers enter the picture. Policymakers are more likely to choose a policy if they understand the causes of the problem and consequences of policy decisions (Stave, 2003; Voinov et al., 2016). This can be achieved through building models that develop a deeper understanding about the complexity in the policy being addressed (Cockerill et al., 2009; Inam et al., 2017b; Stoutenborough and Vedlitz, 2014). Models communicate policy consequences through a flexible platform that enables inexpensive virtual evaluations and assessments, and answer "what if" questions without experiencing their implications in real-world. While models must retain enough characteristics of the issue being addressed they also must be understood and trusted if they are to be utilized by policymakers (Basco-Carrera et al., 2017b). One way for policymakers to gain confidence in a model is to formally participate in the process of making it through means of collaborative modeling (Basco-Carrera et al., 2017a; Burgin et al., 2013; Halbe et al., 2018; Inam et al., 2015; Palmer et al., 2013); ideally, they are then more confident in embracing the model and its results. This process is however time intensive in many stages and it is unlikely that policymakers are willing to spend time with modelers selecting the elements of the real-world system that should be built into a model or define its boundaries.

Ideally, modelers can provide policy decision support, given the right developed tools (i.e., models) and selection among appropriate options (a catalogue of policy alternatives). Modeling can then answer questions and identify trade-offs or questions for further investigation, and policymakers can exercise their political will in adopting the appropriate policy. In reality, however, modelers are challenged by, 1) a lack of appropriate data to build, calibrate, and validate their models (Capalbo et al., 2017; Janssen et al., 2017), 2) the inability to model certain system characteristics or policies because appropriate tools or understanding are lacking, or because of uncertainty in the existing data or model results; and 3) the uncertainties in responses to policy instruments, such as unpredictable responses of water users to conservation measures (for wider discussions and examples see (Bach et al., 2014; Berbel and Mateos, 2014; Brown et al., 2015; Dumont et al., 2013; Harou et al., 2009; House-Peters and Chang, 2011; Liu et al., 2008; Nieuwoudt and Armitage, 2004; Turral et al., 2005)).

For water resources modelers and researchers, lack of access to information, or funding (Brown et al., 2015), and working in isolation from decision makers likely to result in a baffling question for modelers to answer: '*What interventions do we model?'* Consequently, they are often left with scan the literature, including grey literature (e.g. governmental reports or policy plans memorandums), for the most appropriate policy for a specific water issue and most likely, the most studied policy intervention. That potentially results in many studies emerging towards a few subjects (e.g. installation of indoor low flow fixtures or water pricing), whilst others underserved (e.g. expansion of extension services for agriculture or implications of increased research and development).

3.3 Methodology

To assemble a pool of water policies at the river basin scale (objective 1), and to find representative examples for each identified policy (objective 2), we undertook a scoping review exercise, following the framework proposed by Arksey and O'Malley (2005). The resulting catalogue of water policy alternatives focuses on means to address water scarcity, and includes 51 policy tools for the agricultural sector, 55 for the municipal sector, and 31 for the industrial water sector.

A scoping review is a category of literature review for which no universal study definition or definitive procedure is established (Arksey and O'Malley, 2005). It focuses on breadth of coverage of a topic rather than depth (see e.g., Colquhoun et al. (2014); Levac et al. (2010); and Rumrill et al. (2010) for definitions and review protocols, Grant and Booth, (2009) for a comparison of 14 review types, including scoping reviews, and Pham et al. (2014) for a review of scoping reviews previously undertaken). The approach is well suited to address topics that are relatively broad in nature, and examines the extent, range, and nature of research activity, and determines the value of undertaking a deeper review (Levac et al., 2010; Pham et al., 2014). It is particularly useful when a body of literature "*exhibits a complex or heterogeneous nature not amenable to a more precise systematic review*" (Peters et al., 2015, p.141), and "*is less likely to seek to address very specific research questions nor, consequently, to assess the quality of included studies*". Our scoping study addressed the first and second objectives through two questions: Which policy tools have been applied in the agricultural, municipal, and/or industrial sectors to address water scarcity/shortage? Which studies provide representative examples of successful quantification of their effects through computer models?

We searched a number of databases, including Google and Google Scholar, JSTOR, Scopus, and Web of Science and the search engines of publishers including Elsevier (Science Direct), Springer (SpringerLink), Taylor & Francis (Taylor and Francis Journals Online), and Wiley with a large range of keywords (see section 1 in supplementary material). Both peer-reviewed and grey literature were targeted. No time frame was specified, and only electronic sources written in English were accessed. Two sequential searches were conducted, one focusing on policy alternatives for water scarcity, and the other focusing on computer modeling of the policy measures. The first searches produced a comprehensive list of water policies from both peer-reviewed and non-peer reviewed literature. The second searches filtered the results from the first step for the occurrence of the wildcard, "*model**". Finally, we searched all databases and Google Scholar to gather literature on computer modeling of water policies.

Study selection had four stages. First, search lists obtained from the different databases were combined and duplicate studies were removed. Next, both the title and keywords of the source were reviewed. If the key words and title matched the objectives, the study would move to stage two. Second, the abstract was reviewed for correspondence to either of the scoping questions. Third, where study titles, keywords, or abstracts fit the scoping questions, the full-text paper was retrieved. An in-depth review was then conducted to evaluate retrieved studies in terms of 1) water sector(s) and policy option(s) addressed, and 2) the modeling methodology employed (where applicable), including the modeling technique and the types of mathematical relationships used to represent the policy option(s). Fourth, to address the possibility that our searches had not captured relevant studies, we reviewed the references listed in the retrieved studies to identify further articles for review. The review process was iterative, and searches continued until duplications in the retrieved search results outweighed new information such that no significant new material could be obtained. No target number of studies was defined at the beginning of each search to avoid limiting the number of possible water policy alternatives or modeling studies identified.

3.4 A Pool of Water Policy Alternatives

3.4.1 Agricultural water policy alternatives

Population growth, changes in dietary habits, and uncertainties associated with climate change are all increasing pressure on agricultural water demands (Erisman et al., 2008; Godfray et al., 2010), driving a realignment of water management efforts towards a combination of both supply- and demand-side policy measures (Rosegrant et al., 2009). Agricultural water uses are mostly for irrigation to sustain crop production and livestock. Therefore, most water policies in agriculture target irrigation demands and withdrawals.

Agriculture models span a wide range of applications and domains, including policy assessment. Quantifying water demands and withdrawal in irrigation agriculture involves accurate crop modeling and soil moisture simulations. This can be achieved using process-based crop growth models or sometimes statistical regression methods. Agricultural models are often a result of the integration of crop models with other models, depending on the scope of analysis. Such analyses may include effects of salinization on irrigated lands (Saysel and Barlas, 2001), of irrigation practices (Azmi et al., 2012), of rehabilitation of irrigation networks aimed at improving the irrigation utilities (Tehrani et al., 2012), of nitrogen taxation (Berntsen et al., 2003), of extension services to farmers (Carberry et al., 2002), or food security (Carberry et al., 2013). Giuliani et al. (2016) used an integrated model to quantify the impacts of several adaptation water policies including crop mix changes and efficiency changes on water demands under climate change. Rajagopalan et al. (2018) used a simulation model that coupled a crop model with a hydrologic model to simulate crop yields and the associated water demands under climate change. Kuil et al. (2018) developed a socio-hydrological model to study crop change patterns and showed that near-optimal crop patterns can emerge when farmers were to make use of simple decision rules with diverse perceptions on water availability. Gunda et al. (2018, 2017) developed a system dynamics model to understand the effects of seasonal climate forecasts on crop mix diversification. Further, Turner et al. (2017) also used a simulation model to investigate the impacts of agricultural land transformations in the north-central United States. Buchholz et al. (2016) used a simulation gaming model to analyze the impacts of irrigation water policies at the farm level. These studies suggest that the estimation of water demands and potential saving from a specific policy alternative can be more suitably approached through simulation models for the agricultural water sector.

In terms of agricultural water policies, Richter et al. (2017) identified thirteen water conservation measures for irrigated agriculture and their possible water savings. Iglesias and Garrote (2015) reviewed strategies to lessen agricultural water scarcity for European countries and catalogued them by action scope level, timescale, technical difficulty, and potential cost and benefit. Iglesias et al. (2011) assessed eight supply and demand management options to adapt to climate change in the Mediterranean region. The study provided a summary of policy suggestions based on the severity of scarcity. Pereira et al. (2009) listed 18 water conservation measures and their relative importance to cope with water scarcity regardless of the water sector. Similarly, Hamdy et al. (2003) presented a smaller list of measures to cope with agricultural water scarcity through infrastructural and technological changes, and the use of unconventional supplies. Likewise, other potential water adaptation measures to climate change were also listed for the agricultural sectors of Canada (Smit and Skinner, 2002), China (Yang et al., 2007), and Ethiopia and South Africa (Bryan et al., 2009). Other studies focused on the barriers to policy implementation, including structural, financial, environmental, and social barriers (Brown and Hess, 2017; Eisenack et al., 2014; Mukheibir, 2008; Pereira et al., 2009). Others examined the socioeconomic challenges to adaptation practices in Tanzania (Below et al., 2012), Uganda (Hisali et al., 2011), Ethiopia (Deressa et al., 2009), and Australia (Wheeler et al., 2013).

Table 3.1 catalogues 51 agricultural water policy alternatives that address water scarcity in agriculture, promote water conservation, and sustain productivity during water shortages. For each policy, the table references relevant studies (112 in total, with a full bibliography in the Table S1 in the supplementary material) and indicates the typical spatial and temporal scales of analysis for each policy. The "spatial scale" reflects the scale of effect of each policy measure, while the "temporal scale" classifies policies based on the time required to observed effects, timed from the moment of application; effects that require a single growing season to become apparent are indicated by the key word "season", while those that require longer are indicated as "multi-season".

Table 3.1. Agricultural water policy alternatives with a number of identified modeling studies

Spatial scale	**Temporal Scale**	**Policy measures**	**Study count** [1]
Agricultural research and development			
	Multi-season	1. Advances in water application technologies and irrigation machinery	3
		2. Advances in agronomy, crop genetics, and drought resistant crops	
		3. Advances in soil water conservation instruments and methods	
Alternative water supply			
Basin	Season	4. Extraction and use of groundwater	3
Basin	Season	5. Desalination of brackish groundwater and seawater	2
Basin	Season	6. Implementation of wastewater treatment, recycling and reuse programs	4
Basin	Season	7. Activation of inter-basin or regional water transfers	3
Extension services and educational programs			
Basin	Multi-season	8. Delivery of educational programs on water saving technologies	3
Basin	Multi-season	9. Communication of agricultural water conservation programs	
Basin	Multi-season	10. Implementation and/or expansion of agricultural extension services	
• **Irrigated land areas management**			
Basin	Season	11. Restriction of irrigated land-area expansion	2
Basin	Season	12. Conversion of irrigated land to dryland or reduction of irrigated lands	3
• **Irrigation reservoir management**			
Basin	Season	13. Modification of reservoir operating rules for irrigation water users	6
• **On-farm irrigation infrastructure improvement**			
Farm	Season	14. Use of high-efficiency irrigation application systems	7
Farm	Season	15. Adoption of wireless real-time monitoring and automated control irrigation systems	5
• **Water conveyance system improvement**			
Basin	Season	16. Rehabilitation of existing conveyance systems to reduce evaporation and/or seepage losses	4
Basin	Season	17. Rehabilitation of existing control and pumping structures	1

Basin	Season	18. Adoption of wireless real-time monitoring and automated control systems	1
Basin	Season	19. Installation/improvement of gauges and flow measurement devices	1
• **Changes to water property rights**			
Basin	Multi-season	20. Proportional reduction: allocation of seasonally available water proportionally to all users rather than allocation by existing water rights	2
• **Water storage infrastructure**			
Basin	Multi-season	21. Construct on-stream and/or off-stream storage facilities	2
Basin	Multi-season	22. Rehabilitate existing reservoirs to operate at design capacity	
Basin	Multi-season	23. Expand existing reservoirs and storage capacities	1
Basin	Multi-season	24. Utilize deep aquifers for water storage	1
Farm	Season	25. Construct water banking systems and small-scale water reservoirs on farmlands	1
• **Incentives for water conservation**			
Basin	Multi-season	26. Provide incentives for water conservation efforts such as low-interest loans, subsidies, tax breaks, credits, and grants	6
• **Water pricing**			
Basin	Season	27. Attach a flat rate for each unit-volume of water diverted	9
		28. Attach a non-volumetric fee (per output, input, area, or based on land type)	
		29. Apply a tiered water rate structure	
• **Water trading**			
Basin	Multi-season	30. Establish/reform water markets and/or transfer water entitlements temporarily	4
• **Changes in cropping strategies**			
Farm	Season	31. Broaden and diversify crop mixes	3
Farm	Season	32. Grow low-water-use crop varieties	1
Farm	Season	33. Use drought-tolerant crops	2
Farm	Season	34. Change crop seeding times and rates	2
Farm	Season	35. Alter cropping seasons, cropping sequence and tillage	1
Farm	Season	36. Introduce higher yielding varieties	1
• **Irrigation management practices**			
Farm	Season	37. Use accurate demand-based irrigation scheduling	6
Farm	Season	38. Apply soil moisture conservation measures such as mulching, terraces, wind breaks, conservation tillage, and land levelling	6
Farm	Season	39. Implement deficit irrigation	4

• **Irrigation water rationing**			
Basin	Season	40. Apply mandatory restrictions of water diversions for irrigation purposes	3
Basin	Season	41. Encourage voluntary reductions in water diversions	
• **Livestock management**			
Farm	Season	42. Reduce water requirements for livestock	1
Farm	Multi-season	43. Reduce livestock inventory	1
Farm	Season	44. Change feed composition for lower water intensity, import feed from other regions	1
Basin	Multi-season	45. Shift towards mixed crop-livestock systems	1
Basin	Multi-season	46. Reduce consumption of animal products	1
Basin	Season	47. Relocate livestock farms to less water-scarce areas	
• **Return flow management**			
Basin	Multi-season	48. Set return flow requirements for permitted water diversions	1
Farm	Season	49. Construct/improve drainage systems	
Farm	Multi-season	50. Provide incentives for higher returned water flows	
• **Virtual water trading**			
Basin	Multi-season	51. Import water-intensive crops rather than growing them	3

[1] Bibliographical details are provided in the supplementary material

3.4.2 Municipal water policy alternatives

Municipal water use is typically divided into categories based on client type: residential, industrial, commercial, institutional, and public (Mayer et al., 1999). While industrial, commercial, and institutional demands vary according to the nature of the specific clients – whether they produce foods and beverages or metals or operate golf courses – their water use is essentially predictable, based on long-term averages. Most municipal water policies target residential water use, which typically accounts for the majority of the water used by a municipality. Municipal end-uses of water include toilet, shower and bath, laundry, kitchen, “other” (water softeners and humidifiers), and outdoor uses, as well as leaks (Coomes et al., 2010; Mayer et al., 1999). The associated water conservation policies include adoptions of “low-flow” fixtures and appliances, educational campaigns, water metering and consumption feedback, leak detection programs, economic incentives, xeriscaping, and water treatment and reuse (DeOreo et al., 2016; Sønderlund et al., 2016).

End-use based water models offer the best means of analyzing the effects of municipal water policy measures. A wide range of methods can be used to quantify municipal water demands, with the selection depending on modeler skill, available resources and data, and accuracy requirements (Wang and Davies, 2018). Common modeling approaches include the development of statistical regression-based models (e.g. econometric), optimization, and simulation.

Statistical models include regression approaches and econometric models. They are relatively straightforward to develop; however, they are less useful for policy assessment and for understanding cause-and-effect relationships as they assume that historical behavior will continue in the future which may not be true. Econometric models are effective, but they seldom represent the spatial and temporal heterogeneity of water demands (Cominola et al., 2015), and they require extensive and credible cross-sectional and time-series data. Further, these models assume that past trends will continue in the future (Donkor et al., 2014). Arbués et al. (2003) provide a detailed review of econometric residential water demand modeling.

Optimization models involve maximizing benefits or minimizing total costs subject to meeting target water savings or security level (Friedman et al., 2014). They have been used with various levels of complexity in municipal water management (Cahill et al., 2013; Escriva-Bou et al., 2015). Finally, simulation models that include integrated econometric models are more likely to be used for long-term analysis (Donkor et al., 2014; Herrera et al., 2010). They allow exploration and analysis of a range of possible future scenarios and can identify and potentially reduce uncertainties. See Wang and Davies (2015), Willuweit and O'Sullivan (2013), and Dawadi and Ahmad (2013) for examples of simulation models. Dunn et al. (2017) argue that current approaches to municipal water management would benefit from more comprehensive and integrative modeling practices, such as holistic systems approaches. See House-Peters and Chang (2011) and the references therein for a review of the methodological advances for statistical and dynamics urban water demand modeling.

Understanding the effects of available municipal water conservation policies is critical in selecting the most appropriate set. Further, quantifying these effects requires an understanding of the factors that influence household water consumption and the behavior of residents (March and Saurí, 2009) – many water conservation measures involve both technological and behavioral components. For example, the average volume per toilet flush is a technological variable, while the number of toilet flushes per person per day is a behavioral variable. Other factors that influence water use include weather conditions and variability, demographics, socioeconomic factors (age, gender, and income and educational level), and the characteristics of residential indoor and outdoor appliances and fixtures (Cahill et al., 2013). Further, the effects of some policy alternatives are case-specific. For instance, Grafton and Ward (2008) recommended volumetric water pricing rather than rationing in urban Australia, while Zarghami and Akbariyeh (2012) showed water pricing to be unsuitable for Iran. They also found that installing water conservation fixtures and leakage detection would not significantly reduce demand, as did Moglia et al. (2010) for Tarawa, Kiribati; however, these results contradicted those of Grafton and Ward (2008). Finally, different households may adopt water conservation measures for different reasons. Smith and Patrick (2011) found, for example, that motivations for xeriscaping in Canadian households were not necessarily related to water conservation but rather could depend on landscape aesthetics and physical activity.

A number of studies have developed lists of municipal water policies. Neale et al. (2007) listed six demand-side management options, including their expected water savings and cost of implementation. Byrnes et al. (2006) reviewed 21 tools to address limited supplies in Australia. Inman and Jeffrey (2006) reviewed five residential demand-side management tools and the factors influencing their effectiveness in developed nations.

Table 3.2 catalogues 55 municipal policy alternatives that address technological and behavioral aspects of both water supply and demand. For each policy, the table references relevant studies (97 in total, including 87 quantitative and 10 qualitative studies, with full bibliography in Table S2 in the supplementary material) and categorizes the quantitative studies in terms of three general modeling approaches: regression-based econometric models, optimization models, and simulation models.

Table 3.2. Municipal water policy alternatives

Potential policy			
Anticipated impact	**Policy measure**	**Modeling method/approach**[1]	**Study counts**
Indoor water management (Demand/technological)			
Reduce residential indoor water consumption	1. Install low-flow toilets, faucets, and showerheads 2. Use water-efficient washing machines and dishwashers 3. Retrofit existing indoor fixtures and/or appliances	S/SD	2
		O/Two-stage stochastic	2
		S/ABM	3
		S	1
		E/Panel data	1
		E/Monte Carlo	1
		E	1
Xeriscape landscaping (Demand/technological)			
Reduce residential outdoor water consumption	4. Replace conventional lawns with xeriscape landscapes	S	3
		O/Two-stage model	1
		Regression	1
Outdoor watering management (Demand/technological)			
Reduce residential outdoor water consumption	5. Improve residential irrigation: install smart irrigation controllers with moisture sensors and/or timers	S	1
		O	1
	6. Ban sprinkler use; require hand-watering 7. Allow sprinkler use on specific days	O	1
	8. Install artificial turf 9. Cover swimming pools 10. Reduce/restrict car washing or use water buckets 11. Prohibit filling swimming pools 12. Reduce/restrict lawn watering 13. Regulate lawn/garden watering to be in the early morning or at night 14. Restrict the use of water-thirsty plants	S	1
		E/Time-series intervention analysis	1
Alternative water supply (Supply/legislative, technological, operation)			
Augment water supply through unconventional water sources or through expansion of existing supply	15. Transfer water from other sectors, municipalities, or basins	S/SD	1
		S/ABM	1
		O	1
	16. Extract and utilize groundwater 17. Bank water in aquifers	O	1
	18. Desalinate seawater	S/SD	1

	19. Desalinate brackish groundwater	S	1
	20. Build/enlarge supply structures (e.g. dams)	-	-
	21. Activate water markets/transfer water rations	O	1
		O/Two-stage stochastic optimization	1
	22. Collect and use storm water for residential outdoor demands		1
Rainwater harvesting (Supply/technological)			
Increase water supply by harvesting rainwater	23. Collect rainwater through rooftop tanks or rain barrels for indoor and outdoor non-potable uses	Review	1
		S/ABM	1
		Regression analysis	1
		S	4
		S/probabilistic analysis	1
		S/SD	1
		O	1
		Regression analysis/ multivariate ordinary least squares	1
Leak detection and control (Demand/operation and maintenance)			
Decrease water loses from leaking indoor or outdoor system fittings	24. Implement leak detection programs and fines on liable households	Review	2
		S/SD	2
		S/ABM	2
	25. Rehabilitate water distribution networks/Repair detected leakage in water distribution systems and fire-fighting hydrant systems	O/Genetic algorithm	1
		S	1
		O/Hybrid multi-objective algorithm	1
	26. Reduce/manage pressure to reduce unexposed water leakages		
Water metering (Demand/legislative)			
Drive behavioral change through the provision of water use details	27. Install smart meters to monitor water use	Review	*3*
		E/Panel data analysis	1
		S/SD	1
Urban water management R&D (Demand/Supply/education)			

Drive long term reduction of urban water consumption	28. Research urban water scarcity and drought planning and mitigation strategies 29. Invest in data collection surveys and monitoring networks for accurate water use calculations and modeling 30. Invest decision-support tool development 31. Invest in water conservation technologies	-	-
Water reclamation, recycling, and reuse (SSM/operation and maintenance)			
Increase water supply through greywater reuse	32. Recycle and reuse previously consumed potable water (grey water) 33. Use partially treated/recycled wastewater to irrigate playing fields or golf courses	S/SD S/ABM O/Two-stage optimization	1 1 1
Education and public awareness (Demand/education)			
Use public information and awareness campaigns on water conservation to drive behavioral changes	34. Reduce toilet flushes	PA S/ABM S	1 1 1
	35. Reduce shower durations	S/Mathematical Material Flow Analysis S	1 1
	36. Reduce shower frequency	S/ABM Hybrid/analytical-regression	1 1
	37. Reduce faucet use 38. Provide more informative water bills 39. Consolidate laundry loads 40. Run only full loads in dishwashers	Discussion S/ABM S/Mathematical Material Flow Analysis E/Panel data S/SD	1 2 1 1 1
Population control (DSM/legislative)			
Decrease total water consumption based on the number of water users/household	41. Control population stock through reducing immigration rates	S/SD S/ABM	1 1
Water pricing (DSM/financial)			
Regulate water consumption through changes in water price	42. Use block rate tariff schemes (steeply increase block rates to penalize water use above a certain level)	E/Marshallian surplus E/Discrete-continuous choice model	1 1 1

	43. Increase water charges per unit volume	E/Two-stage least squares	1
	44. Use seasonal or peak-price tariffs	Discussion	*1*
		S/SD	2
		E	2
		O/Two-stage stochastic optimization	1
		S/ABM	2
Water rationing (DSM/legislative)			
Ration water to households based on a limited supply	45. Ration water by fixed allotment	E/Marshallian surplus	1
	46. Ration water by percentage reduction	E/Generalized method of moments	1
	47. Ration water by service outage (rotational water cut-offs)	E	1
		S/SD	1
	48. Ration water by type of use	Discussion	*1*
Incentives and rebates programs (DSM/legislative, financial)			
Motivate adoption of water conservation measures	49. Develop and implement rebate programs for retrofits and the installation of low-flow fixtures and/or water-efficient appliances	Survey	*3*
		S/ABM	1
	50. Provide cash incentives/subsidies/tax credits for fixtures upgrades		
	51. Use non-financial strategies such as norm-based messages and social comparisons		
Regulations (DSM/legislative)			
Reduce both indoor and/or outdoor household water consumption	52. Prohibit the sale of single-flush toilets and other similar fixtures	Discussion	1
		S/ABM	2
	53. Penalize unregistered water uses		
	54. Require a permit to fill pools		
	55. Implement efficiency regulations for new buildings		

[1] S: Simulation;
O: Optimization;
E: Econometric/Regression-based;
SD: System Dynamics;
ABM: Agent Based Modeling

3.4.3 Industrial water policy alternatives

Industries use water for food and beverage production, washing and cleaning in processing facilities, steam generation and condensing, as well as for diluting or transporting purposes

(Gu et al., 2014; Statistics Canada, 2012). The exact quantities of water used are often difficult to determine, both because industrial water use data are often aggregated into total water withdrawal values by sector, and because industries self-supply much of the water they use, so that plant-specific usage is rarely publicly available (Dupont and Renzetti, 2001). For example, in Canada, 75% of industrial water use is self-supplied, according to Statistics Canada (2012). Unlike the agricultural sector, the industrial sector consumes only a small fraction of its withdrawals.

Industrial water use can be divided into three categories: manufacturing, power generation, and mining and oil and gas extraction. We present water management strategies and policy measures that aim to minimize water use in industry and increase efficiency. Note that although reducing industrial water use is beneficial, it can also result in increased concentrations of chemical contaminants released into the environment (Qin et al., 2015). Therefore, both water use and supply are linked to water quality, and water contamination contributes to water scarcity, hinders development, and poses a threat to ecosystem sustainability (Bakker, 2012; Cook and Bakker, 2012).

Modeling policy assessment studies in terms of industrial water uses and demands are limited and are mainly concentrated in the concepts of energy-water nexus (DeNooyer et al., 2016; Khan et al., 2017; Lubega and Farid, 2014), and water-food-energy nexus (Qin et al., 2015; Uen et al., 2018).

Table 3.3 catalogues 31 industrial policy alternatives that address the technological and behavioral aspects of both water supply and demand. For each policy, the table references relevant studies (28 in total, including 22 quantitative and 6 qualitative studies) with a full bibliography in Table S3 of the supplementary material.

Table 3.3. Industrial water policy alternatives

Policy			
Policy purpose	**Policy measure**	**Study type**	**Study counts**
Electricity supply management			
• Decrease water use for electricity generation	1. Exchange power between utilities 2. Conserve energy to decrease water use	Review Input-output model	1 1
	3. Trade electricity with other regions	S	1
	4. Close older, less efficient small-scale power plants	S, O	1
	5. Decommission coal-fired in favor of natural gas plants	O	1
Alternative water supply			
• Augment current water supply or explore new supply	6. Increase on-site water storage capacity/water banking	Review O	1 1
	7. Permit water markets/transfers between utilities in the same or different sectors in one basin, or allow inter-basin transfers 8. Reuse municipal greywater or agricultural drainage/runoff water 9. Use fresh or brackish groundwater 10. Reclaim produced water, and reuse or redistribute internally-generated wastewater 11. Replace fresh water used for drilling and well completion activities with saline water 12. Study the water storage capacity of groundwater aquifers	S Review	2 1
Improved water efficiency and adoption of new technologies			
• Increase the efficiency of water use, or increase water productivity (unit	13. Increase cycles of concentration in power plant cooling systems	O S	1 2

output per unit of water input)	14. Reduce evaporative losses in power plant cooling towers 15. Adopt dry or near-dry mining technologies 16. Improve water productivity in the oil and gas industry (CO_2 injections, polymer floods, and fire floods) 17. Adopt water-efficient cleaning, processing, and operating methods for manufacturing 18. Implement solvent injection to enhance water recovery 19. Upgrade equipment and operating procedures to increase water productivity		
	20. Change power plant cooling technology	S S, O	3 1
Provide incentives			
• Use financial incentives to drive behavioral changes	21. Utilities pay for energy efficiency and conservation activities, load reduction during peak demand, and interruptible-load 22. Use financial incentives to drive efficient water use practices: tax adjustments or rebate programs	Review	2
Water loss management			
• Decrease water use for fuel transportation and facility operations	23. Reduce cooling tower evaporation losses through coal drying and other technologies 24. Detect and repair leaks in distribution systems	Review S	1 1
Water pricing			
• Use water pricing to drive efficient water use or adoption of conservation measures	25. Increase the volumetric unit price of water 26. Use tiered or increasing block rate water pricing	Input-output model S, O Econometric modeling	2 1 3
Regulatory measures			

• Reduce industrial water withdrawals and increase return flows	27. Impose production limits on food and beverage processing facilities 28. Impose limits on power generation 29. Implement regular leak detection inspections 30. Revise and redefine water quality regulations for the different phases of water use to steer usage of lower quality water if safe 31. Reduce/eliminate freshwater use for oilfield injection	Review	1

3.5 Conclusions

Despite the prominence of policy instruments to unfold concepts to practical applications, they widely diverge across scholarly publications and grey literature. We developed a pool of water policies to respond to water scarcity in the agricultural, municipal, and industrial water sectors and presented the pool from a computer modeling perspective. A scoping review method was employed and extracted 237 studies from which 137 policy alternatives were identified. The policy “menu” has 51 policy interventions for the agricultural water sector, 55 for the municipal, and 31 for the industrial with relevant citations of modeling studies. The pool does not recommend or endorse the use of one policy over the other, but instead, it provides an inventory for modelers and policymakers as a starting point to explore consequences of the different water policy measures. Each management strategy can yield considerably different results and implications based on local conditions, and social, economic, and environmental characteristics of the basin under water scarcity.

Connecting Text to Chapter 4

The system dynamics crop growth model, CropSD, developed and presented in Chapter 2 is integrated with a socioeconomic system dynamics model to describe the feedback mechanisms of the irrigation expansion in Alberta. The model is used to reveal the broader consequences of expanding Alberta's irrigation sector under climate change and under various policy alternatives chosen from the catalogue created in Chapter 3 for the agricultural water sector. The resulting model, called Alberta Irrigation Scenario Simulator (AISS), integrates the biophysical aspects of crop growth with socioeconomic, environmental, and policy choices in one integrated system. The model exchanges information across its different components and scales during runtime, with no external coupling involved. Dynamic relationships between different model variables are presented through mathematical relationships. A complete model description is provided in the form of stock and flow charts presented in Appendix A. All equations of auxiliary variables, levels (stock), data, constants, lookup functions, and subscripts are also provided in Appendix A.

Chapter 4. Future Irrigation Expansion in the Presence of Feedbacks at the River Basin Using Process-Based Integrated Systems Modeling

4.1 Introduction

Agricultural water problems span a wide range of connections between land and water, weather variability, increases and shifts in demands, socioeconomic changes, and climate change and policy factors. Such connections are complex, poorly understood and unpredictable, and therefore are often dealt with in isolation. The demand for tools that can assist in the analysis of these complex agricultural problems is a necessity (Holzworth et al., 2015) and the need for dynamic interconnected modeling and quantitative approaches that go beyond the sole aspects of crop biophysical responses and irrigation scheduling is a key requirement to solving such complexities (Ahuja et al., 2007; Donatelli et al., 2010; Uthes et al., 2010). According to Ewert et al. (2014, p.290), "*crop model studies treat climate, soils and management factors as exogenous input variables to the system and do not account for dynamic feedbacks between crop productivity and input variables*"; this lack of feedbacks has also been noted in other studies, see (Bezlepkina et al., 2011; Carberry et al., 2013, 2002; Kersebaum et al., 2015; Rickards and Howden, 2012; van Delden et al., 2010; van Ittersum et al., 2008).

There has been an emerging trend in agricultural modeling towards broadening the scope and coverage of cropping systems models to include new and wider domains such as climate change assessment and adaptation (Aurbacher et al., 2013; Bassu et al., 2014; Ewert et al., 2015; Lehmann et al., 2013), food security (Carberry et al., 2013; Godfray et al., 2010; Tubiello and Ewert, 2002), and agricultural and water policy assessment (Bryan et al., 2011; García-Vila et al., 2009; García-Vila and Fereres, 2012; Therond et al., 2009). Despite this trend, there has been less emphasis on developing agricultural models with integrated, feedback-driven, and dynamic characteristics that can be applied for macroscopic policy assessment over long temporal scales and under climate change (Ewert et al., 2015). There is thus great potential for further development in agricultural models for underserved areas including water-food-energy nexus, policy assessment, and climate change adaptation and assessment (Antle et al., 2017a; Holzworth et al., 2015; Janssen et al., 2017; Jones et al., 2017a).

For agricultural policy assessment, model development can potentially be approached through system dynamics (SD) modeling (Antle et al., 2017b; Capalbo et al., 2017; Reidsma et al., 2018; Turner et al., 2016a). SD provides a potential solution by integrating information from various disciplines into a single and comprehensive modeling framework that is capable of capturing, and quantifying, cause-and-effect relationships, both explicit and implicit feedback structures of a problem (Mirchi et al., 2012). Therefore, the dynamics and the complexities of the modeled system can be represented, especially those commonly encountered in policy assessment. Moreover, the issue of simulating carryover effects across years is important for the adaptation and policy assessment in order to allow effects or policy measures to accumulate and emerge, and for any unforeseen consequences to become tangible.

The irrigated agriculture sector in Alberta, Canada is an example of the competing interests for increasingly limited water supplies, ongoing socioeconomic developments, and future changes in climatic regimes, and thus uncertainties of future water availability, agricultural production, and the overall water demands of the irrigation sector. Further, there is interest from both agricultural policymakers and irrigation managers to expand the irrigated land base of Alberta. However, with such competing interests and uncertainties, the assessment of the expansion potential is challenging and implies increased investment risks. Expansion could require the adoption of improved irrigation application systems, the introduction of new crop varieties or changing crop mixes, acquisition of new machinery, and upgrading or expansion of existing infrastructure, or building of new infrastructure (Ammar et al., 2014). Therefore, the uncertainty in future climates and water supply requires testing the capacity of the irrigation sector of Alberta and evaluating the impacts of a changing climate on water demands, given the complexity of the various physical and socioeconomic conditions for future expansion scenarios.

In this paper, we developed the Alberta Irrigated Scenario Simulator (AISS) to explore and quantify changes in an irrigated agriculture system performance corresponding to possible changes in water availability, crop biophysical changes, climate change and weather variability, changes in socioeconomic factors, and policy measures. The work aims to increase the understanding of the potential consequences of irrigation expansion, and to permit assessment of trade-offs associated with different policies. The modeling framework is based on System Dynamics methodology (Forrester, 1961; Sterman, 2000). It integrates a process-based crop growth model with a socioeconomic system dynamics model that describes the irrigation system, making it the first of its kind. The model allows to assess the existing, as well as new cropping systems, and to explore the potential for crop yield improvements, changes in crop mixes, agricultural profitability, and long-term socioeconomic changes. The model combines segments of different scales including fine scale process-based crop growth and the economics of production, as well as long term infrastructure upgrades and shifts in climate. It also includes the social aspects of expanding the irrigation land base or the adoption of improved irrigation technologies into a single model.

Moreover, this study assesses the impacts of climate change on Alberta's irrigation sector in terms of water demands, water withdrawals, changes in crop production, and changes in the irrigation land base. Studies in this area are limited to either the impacts of climate change on yields of individual crops such barley (Langhorn, 2015; Lu et al., 2018; Masud et al., 2018) or the overall irrigation demands (Islam and Gan, 2015, 2014).

The specific questions we aim to answer for our study area by 2040 are:

1- What are the impacts of climate change on the yields of the major crops in Alberta?
2- What is the capacity of Alberta's irrigation sector under current water, structural, and socioeconomic characteristics to future climate?
3- What is the outlook for the irrigation sector under different expansion scenarios, socioeconomic changes, and policy interventions in the presence of climate change?

To address our research questions, we (1) report on the necessity for integrated systems modeling in irrigated agriculture, given the feedback driven behavior, (2) outline the objectives and structure of the developed Alberta Irrigation Scenario Simulator (AISS), (3) assess the model structural validity with a number of conventional and systems-specialized testing, and history matching, (4) demonstrate the application of the model in Alberta's irrigation sector through generating of a number scenario groups for strategic planning. The study contributes to the growing efforts of the agricultural modeling communities to develop models to be applied at a broader scale of time and space that integrate various domains to allow for policy assessment. Another contribution of this study is its attempt to represent and capture intangible, qualitative social aspects of irrigated agriculture in measurable, quantitative valuations represented in decision scores to expand or hold irrigation land areas by water managers and in decision scores to adopt improved irrigation practices and application technologies by irrigators through a Likert scale-like indices. The methodological steps to the development of the system dynamics model are presented in section 4.4.

4.2 State of the Art in Integrating Crop Growth Models for Policy Assessment

4.2.1 Crop models

Crop yield response to water is the core element for any agricultural application. Crop models are used to estimate possible crop yields under available water, changing weather conditions, and agronomic practices. Such crop models can be categorized either as statistical crops models that are defined by a regression production function based on historically observed crop yields and water used over multiple years, or as mechanistic process-based models with functions that describe the various processes of crop growth with a high level of modeling detail.

Statistical crop production response models (e.g. production functions) can be used as inputs to broader scale (spatial and/or temporal) studies that involve long-term bio- or socioeconomic components. They are easily coupled to other economic or hydrologic models to provide insights on historical trends of crop yields (Bennett et al., 2014; Keating et al., 2002; Prasad et al., 2006). These “reduced form crop models” are often developed to represent local agronomic and environmental conditions (Lobell, 2013; Lobell and Burke, 2010). However, they cannot be applied to extrapolate responses that are outside their estimation domain (Jones et al., 2017b), and they cannot capture the effects of increasing atmospheric CO_2 concentrations or long-term changes in temperatures on crop yields (Basso et al., 2015).

In contrast, process-based crop models provide an accurate representation of crop-yield responses to weather, soil moisture and nutrients contents, agronomic practices, and changes in concentrations of CO_2 through deterministic functions. They are the only suitable tool for quantitative assessments of future crop production (van Bussel et al., 2011). Therefore, coupling process-based crop models to other socioeconomic, environmental, or hydrologic models to broaden their application domain for future assessment is inevitable. A variety of dynamic process-based crop models have been developed, many of which are both widely-used and well-established; see Rivington and Koo (2010) and Di Paola et al. (2016) for surveys of process-based crop modeling tools.

4.2.2 Linking crop models in an integrated framework

Linking crop models with other socioeconomic, environmental, or hydrologic models to form an integrated systems model can help to assimilate knowledge and perspectives from different points of view (Janssen et al., 2017; Reidsma et al., 2018). Further, such integrated models can be used to represent the underlying causal structures and evaluate broader consequences in the context of changes in the system drivers (Kelly et al., 2013). They facilitate the understanding of how a system operates, as well as policy assessment to identify future tipping points of the system (Gohari et al., 2013; Turner et al., 2016a), and interventions or strategies for change (Wang and Davies, 2018, 2015).

Methodologically, data exchange within an integrated system may be sequential (or forward-feed), in which one model completes its simulation and produces data for subsequent and different model operation, or it can be iterative (through feedbacks), in which system of models require the exchange of intermediate data values during runtime (Belete et al., 2017). Because agricultural models do not typically span interactions across several domains within a single model, external coupling is always necessary (Holzworth et al., 2015). However, it is not a trivial task to link legacy models, as they were not built for integration but rather for an in-depth understanding of a specific discipline (Kelly et al., 2013), and are often linked by linear sequential thinking using forward-feed data exchange from one model (component) to the other. There are a few exceptions, such as the SEAMLESS project (van Ittersum et al., 2008, 2006), which was developed using a component-based approach to link individual models and data components sequentially: see applications in Bezlepkina et al. (2010) and Therond et al. (2009). The framework developed was project specific (Holzworth et al., 2015), required upscaling of one model result into the next, and focused on large scale regional analyses and policies of the EU. A second modeling framework, IIMF, was used to assess the impacts of climatic and socioeconomic changes on land use changes, including agricultural land changes (Schönhart et al., 2018; Zessner et al., 2017). Its basis was the integration of several well-established models; however, this was accomplished in a linear manner that applied one model's output as the next model's input. Finally, many other studies have used a similar component-based approach (Belem and Saqalli, 2017; Schönhart et al., 2016; van Delden et al., 2010). Such sequential approaches may overcome complexities related to the cross-scale attributes of the different disciplines and domains by means of upscaling (both space and time; like in SEAMLESS project) of data or outputs of individual members of the component-based models (van Bussel et al., 2016, 2015; Van Ittersum et al., 2013; Van Wart et al., 2013). However, they lack the feedback dynamics between the different components of the systems. Therefore, important feedbacks of the problem being analyzed at various scales – for example, irrigation expansion increasing water withdrawals, and thus adding concerns about sustainability to future expansion plans – are not considered. Both the complexity and importance of the feedback driven structure of irrigation expansion in the context of agricultural production systems (see Figure 4.4) demands a quantitative approach that goes beyond the typical scale of predicting crop yield in a field scale and capable of adequately considering feedback loops.

Several studies have used system dynamics (SD) modeling in the context of irrigation water and land management and have included their connections with various socioeconomic, hydrologic, and environmental aspects. For example, Saysel and Barlas (2001) used system dynamics to study the farm-scale environmental effects of salinization on irrigated lands. Another study analyzed the long-term environmental sustainability of an agricultural development project in the Southeastern Anatolian Project–GAP using system dynamics (Saysel et al., 2002). Martínez-Fernández and Selma (2004) used SD to integrate five subsectors including irrigated lands, profitability, available space, water resources and pollution to study the dynamics of water scarcity on irrigated land areas. Their study showed that policies aimed to increase water resources did not eliminate the water deficit because feedback loops in the system simply increased the irrigated land area. Similarly, Elmahdi et al. (2005) assessed the impacts of allocation of limited water resources between agricultural production and the environment in Australia using system dynamics. Their study combined SD with a constrained linear optimization to determine the optimal water use and crop pattern of an agricultural area against two objectives: to maximize the net profit, and to minimize the amount of the irrigation water used (see also: Elmahdi et al. (2006)). Azmi et al. (2012) assessed the impacts of various irrigation practices at a farm level scale on irrigation water shortages using system dynamics. Another study investigated the effects of rehabilitation of irrigation networks aimed at improving irrigation utilities in Iran (Tehrani et al., 2012). Walters et al. (2016) used system dynamics in studying the sustainability of agricultural production systems in three different production regimes with crops only, livestock only, and a combination of both. Inam et al. (2017a, 2017b) investigated several management options to decrease soil salinity and increase farm income. Their study linked a process-based soil salinity model with a socioeconomic system dynamics model, and used MS Excel and Python to facilitate data transmission between the two models. Gunda et al. (2017) developed a SD model to understand the effects of seasonal climate forecasts on the choice of farms in terms of crop mix diversification. Further, Turner et al. (2017) used scenario based "what-if" questions to investigate the impacts of grassland conversion to row-crop production in the north-central United States. The study employed system dynamics to integrate land quality features, grain and livestock economics, US farm policy incentives, and rural communities. Similarly, Turner et al. (2016b) used SD to build a model to understand the behavior of the acequia irrigation communities of New Mexico to several socioeconomic and biophysical changes. Gunda et al. (2018) coupled the acequia SD model to the upland watershed using a hydrologic model to explore how the community would behave with streamflow conditions expected under climate change.

4.3 Data and Modeling

This section presents the study area, the climate change data and projections for the future using a physically-based distributed hydrologic model, the projected streamflow data used as future water supply, and finally the data used to steer the system dynamics model. The model developed in this study applies a systems approach, using the system dynamics (SD) methodology. Systems approaches are suitable for agricultural policy analysis because of the complex, multidimensional nature of policy problems that involve human behavior. Flexibility is a key asset of system dynamics modeling, allowing future functionality expansion through the inclusion of other processes. Our model builds connections among biophysical, socioeconomic and policy considerations in one integrated unit. It approximates the reality of complex irrigated agricultural systems by formulating the model to perform as a whole-system, in which all components are tightly coupled through explicitly closed feedbacks. Further, a detailed, process-based crop growth model is at the core of an integrated basin scale agricultural systems model. The well-established process-based FAO's AquaCrop model (Raes et al., 2009; Steduto et al., 2009) was translated into SD framework and was integrated into a socioeconomic irrigated agricultural systems model.

4.3.1 Study area

Irrigation in Alberta is the largest consumer of surface water (Islam and Gan, 2016) and a key economic driver. The irrigated area within the province represents 65% of the total irrigated area in Canada and is concentrated in the southern part of the province, particularly in the South Saskatchewan River Basin (SSRB). The basin has a semi-arid climate with annual precipitation between 200 mm and 500 mm (Martz et al., 2007). About 70% of the annual basin runoff is supplied from the Rocky Mountains and foothills (Ashmore and Church, 2001) primarily through spring snowmelt (Tanzeeba and Gan, 2011).

Irrigation is concentrated in 13 irrigation districts (Figure 4.1) of which three are in the sub-basin of the Bow River, nine are in the Oldman River sub-basin, and one is in the South Saskatchewan River sub-basin. In 2006, the Alberta government closed the basin to new water licenses (Alberta Environment, 2006), challenging future irrigation expansion along with projected changes in the water supply under climate change (Islam and Gan, 2014).

Despite these limitations, Alberta's irrigation sector has expanded considerably in the last two decades and will likely continue to grow because of its social and economic values to the province (see supporting information in the supplementary material section 1). To meet demands, the sector has undertaken several water conservation measures (Bennett et al., 2017, 2015) including adoption of low center pivots and converting irrigation canals into closed pipelines. Opportunities for irrigation expansion, despite the capped water license and closure of the basin to new water allocation, remain promising, but there are also a number of risks and challenges associated with expansion (Ammar et al., 2014). Therefore, it is necessary to explore and understand the irrigation sector and the likely trade-offs and risks associated with any future expansion and compounded with the future impacts of climate change on the basin.

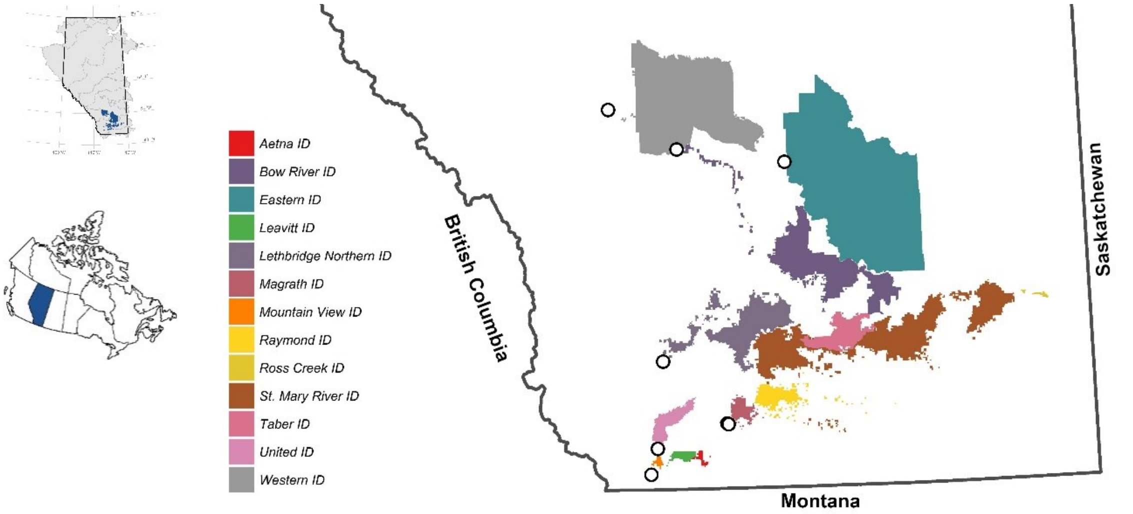

Figure 4.1. The irrigation sector of southern Alberta, Canada. Thirteen Irrigation Districts (ID) are shown in the figure. Circles denote eight locations of the streamflow gauging stations at which the future irrigation water supply is simulated using the hydrologic model

4.3.2 Climate projections using ensemble climate models

To incorporate future changes in both water supply and irrigation demand, we obtained climate projections from the Pacific Climate Impacts Consortium (PCIC) (Cannon, 2015) at a gridded resolution of 300 arc-seconds (~10 km). PCIC provides statistically downscaled

GCM climate scenarios for the period of 2005-2100 (Bürger et al., 2013, 2012) based on the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012) and the historical daily gridded climate data for Canada (McKenney et al., 2011). The models in the PCIC database are forced with the so-called Representative Concentration Pathways (RCPs) to represent three scenarios of future greenhouse gas (GHG) concentrations (see van Vuuren et al. (2011a) for details).

For this study, to reduce the uncertainty resulting from the variability of outputs from different models, an ensemble approach was employed. We incorporated two climate scenarios in an ensemble of five GCMs (i.e. CanESM2, CCSM4, CNRM-CM5.1, CSIRO-MK3.6.0, and MIROC5). Projections were obtained for the near future for the period 2017-2040 based on two greenhouse gas emission (GHG) scenarios: RCP 2.6, and RCP 8.5. The RCP 2.6 scenario indicates a low forcing level with mitigation and corrective policies aiming to decrease the GHG emissions, with a peak of 3.1 $W.m^{-2}$ in the mid-21st century, and limits the increase of global mean temperature to 2°C (van Vuuren et al., 2011b), whereas the RCP8.5 scenario is a high GHG emission scenario, with a rising radiative forcing pathway leading to $8.5W.m^{-2}$ by 2100.

To reflect local climate conditions and variability, the PCIC projections were further downscaled to generate more realistic climate datasets for the model. We applied the delta method, which uses historical climate data sets to produce future time series based on deviations between future and present periods (Quilbé et al., 2008). Changes in mean temperature of the growing season of Alberta (April-August) with the two scenarios, RCP 2.6 and RCP 8.5, are projected to be in the range of 0.9–2.0 °C and 1.4–2.6 °C, respectively, for the 2017–2040 period relative to the 1993–2016 period. Moreover, the projected changes in precipitation are in the range of -8%–+32%, and -14%–+21% for both scenarios, respectively. Reference evapotranspiration ET_0 and aridity index AI showed varying changes during the months of the growing season, as shown in Figure 4.2. Further, growing degree days (McMaster and Wilhelm, 1997) and the accumulated corn heat units showed an earlier accumulation of up to 1 and 2 weeks (Figure 4.3) by the end of the growing season for RCP 2.6 and RCP 8.5, respectively, which indicates a longer growing season and opportunities for growth of new crop varieties. Both growing degree days and corn heat units are measures commonly used by irrigators in Alberta.

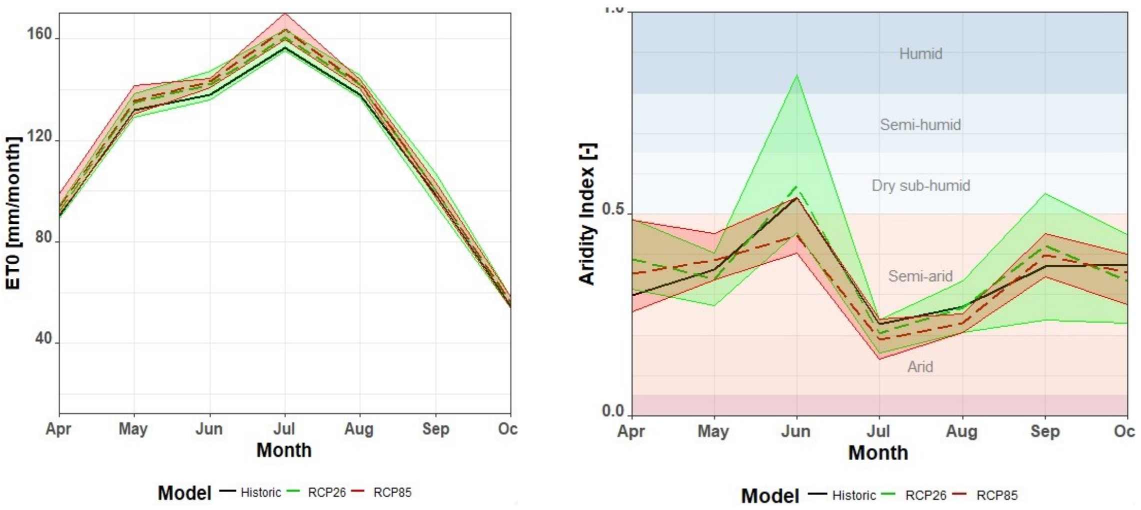

Figure 4.2. Climate characteristic between April through October for southern Alberta, as estimated by an ensemble of statistically downscaled climate models for low (RCP 2.6; green) and a high (RCP 8.5; red) emissions future (near future). Solid lines and shading represent the multi-model mean and range, respectively.

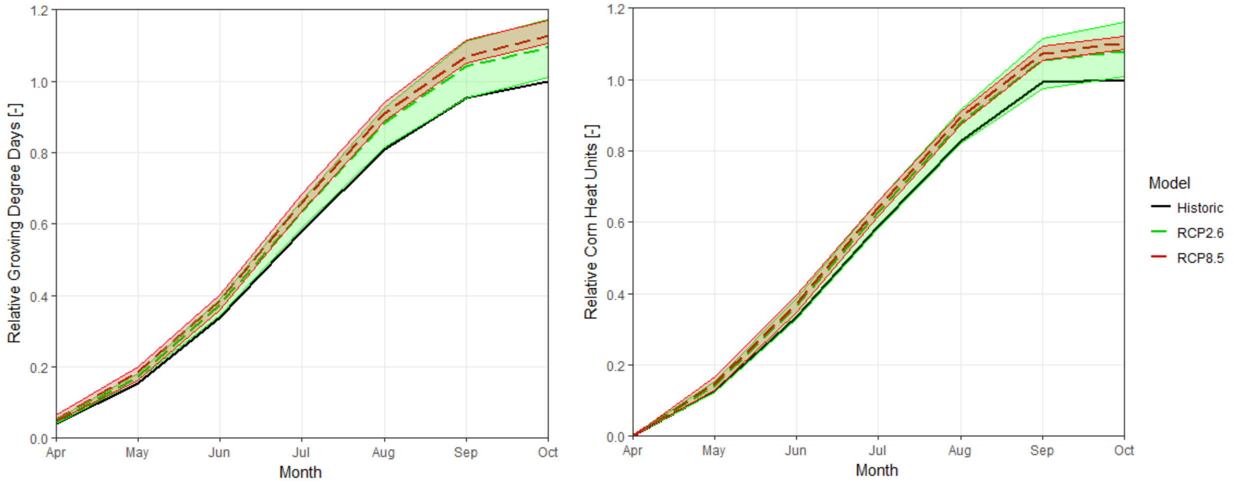

Figure 4.3. Accumulated growing degree days (GDD) between beginning April through October for southern Alberta, as estimated by an ensemble of statistically downscaled climate models for the historical baseline (1993–2016; black) a low (RCP2.5; green) and a high (RCP 8.5; red) emissions future (2017–2040). Solid lines and shading represent the multi-model mean and range, respectively. For instance, towards the growing season by the end of August by the 2030s under the low and high emissions future, the same GDD are accumulated 1 and 1.5 weeks earlier than in the historical baseline, respectively.

4.3.3 Hydrologic model of Alberta

We used a well-established SWAT hydrologic model developed for the province of Alberta by Faramarzi et al. (2017, 2015) to generate the future streamflow for the irrigation sector. The model simulates water supply under the different hydrologic features and climate scenarios for Alberta. It has been intensively calibrated and validated to represent Alberta's hydrology – see Faramarzi et al. (2015) – and has been applied in a number of hydrologic applications (Gharib et al., 2017; Masud et al., 2018). We generated the future simulations by forcing the model with the two future climate scenarios for the study period. The multi-model ensemble simulations were then used as inputs to the water supply component of the systems model developed in the study.

4.4 Alberta Irrigation Scenario Simulator (AISS)

4.4.1 Dynamics hypothesis

Mapping the irrigated agriculture system with a casual diagram facilitates a conceptual understanding of the system, sets its boundaries, captures hypotheses about the causes of dynamics, and shows the feedback loops that affect the behavior of various system elements, key variables, and critical time delays that may rise unexpected consequences (Mirchi et al., 2012; Simonovic, 2009; Sterman, 2000; Winz et al., 2008). The causal loop diagram (CLD) in Figure 4.4 represents the fundamental components of the irrigated agricultural system of southern Alberta. The CLD was developed based on the academic literature and dialogue with stakeholders. Stakeholder involvement was intended to represent multiple perspectives and address stakeholder's key concerns. The dialogue itself occurred at a one-day workshop on 2014 and aimed to improve our insight into the current status and future challenges for expanding the irrigation sector, define the boundaries of the irrigation sector, and set the priorities and the questions of most interest for expanding the irrigated land base in the future (Ammar et al., 2014). Fourteen participants attended the workshop including irrigators, ranchers, irrigation districts managers, economists, government personnel, and business representatives.

The conceptual model in Figure 4.4 consists of five major feedback loops – three reinforcing loops and two balancing loops – that govern the expansion of irrigated agriculture. The economic driver or "*Economic gains*" (reinforcing) feedback loop reinforces the expansion of the irrigation and drives a continuing trend of growth, where the incentive for expanding agriculture is more revenues. The "*Irrigation water supply*" (reinforcing) loop provides a lower risk for expansion, where more supply drives more expansion. The "*Infrastructure*" (reinforcing) loop shows the causal relationship between the irrigation infrastructure that includes building new storage reservoirs or upgrading existing ones (on- and off-stream), and rehabilitation of the diversion and the conveyance structures, thus increasing the reliability of water supply for irrigation and contributing to a decreased water deficit. The "*Water shortage*" (balancing) loop denotes the deficit to the required demand. It counterbalances the effect of the reinforcing loop and balances the continuing expansion. In the case of fixed water supply, increasing the water demand eventually increases the irrigation water deficit, which constrains further expansion. Finally, meeting irrigation demands requires diverting water from the South Saskatchewan River Basin (SSRB). Excessive water diversions threaten the environment and affect aquatic ecosystems. Such effects are represented dynamically in the balancing (balancing) loop "*Environmental pressures*", and the causal linkage between water diversion and water quality in the river. These threats to public health and aquatic life drive public pressure and environmental groups for stricter regulations to safeguard the environment. As a result, water diversions may drop, and water deficits increase, contributing to the water shortage loop.

In reality, system behavior is determined by the dominance of one loop over the other. Continuous growth or decline does not typically occur, but rather the effects of reinforcing loops (balancing loops) are gradually reduced in complex systems through balancing loops (reinforcing loops) that potentially slow (accelerate) the growth, stop it, divert it or even reverse it (Bender and Simonovic, 1996). The conceptual model built with the involvement of stakeholders is the basis for the quantitative system dynamics simulation model presented here. The following sections describe the SD model, its evaluation and assessment, and application for Alberta's irrigation sector with a combination of expansion and policy intervention scenarios.

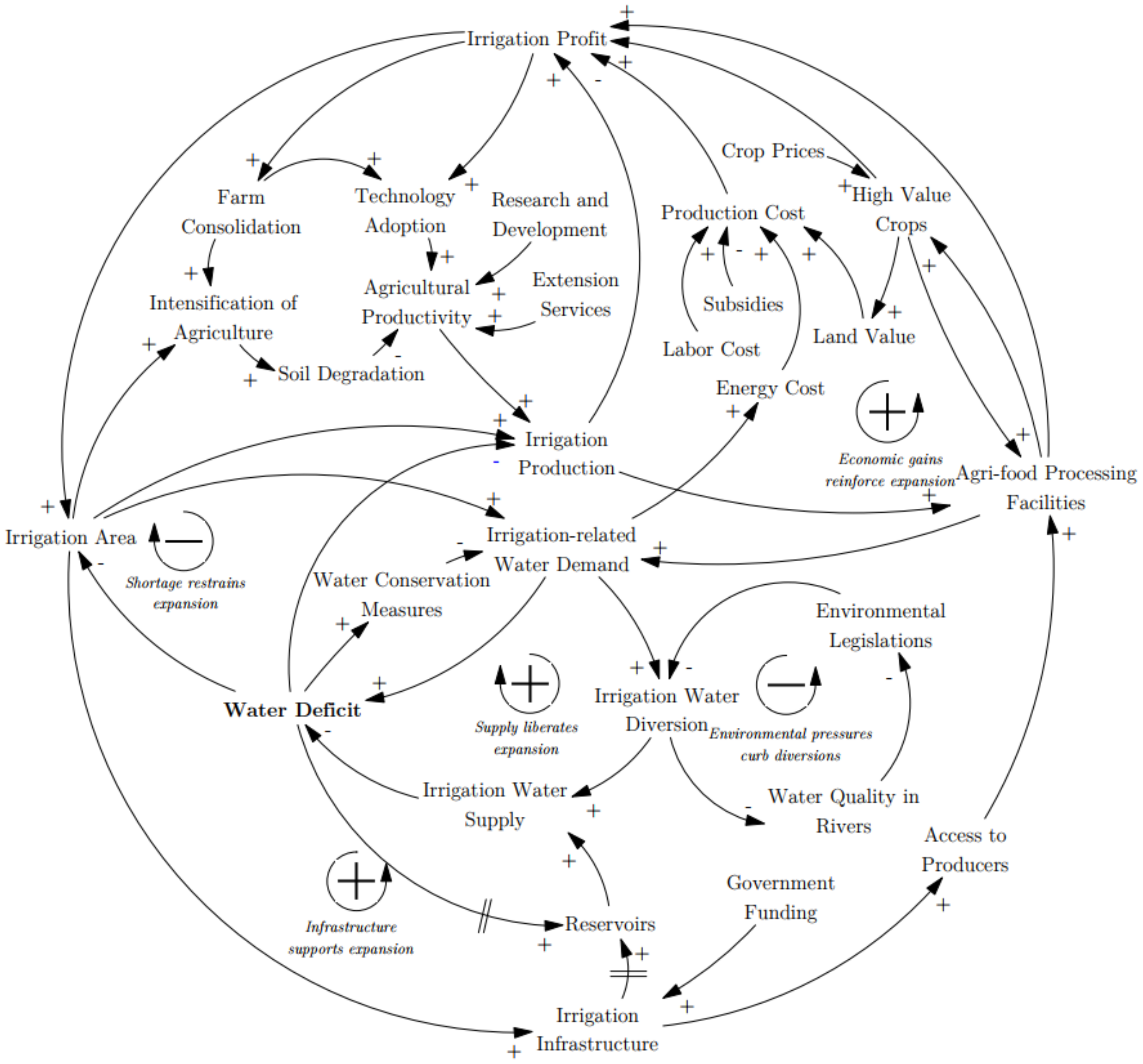

Figure 4.4. High level summary of the dynamics describing the irrigated agricultural sector of southern Alberta as developed integrating both stakeholders group insights and the literature. Polarities on arrows denote the direction of change. A positive (negative) link means an increase (decrease).

4.4.2 SD model components

The Alberta Irrigation Scenario Simulator (AISS) is a system dynamics model that simulates changes in the irrigation sector under a wide range of conditions. Scenarios can include expansion rates, access to the incentive, extension services, infrastructural changes, and changes in storage, and farmers' perceptions of water security under future climate change.

The model consists of five integrated components: (1) a process-based crop growth model, (2) water demand and supply management, (3) irrigation infrastructure changes, (4) crop production economics, (5) socioeconomic responses and policy interventions. AISS operates at a weekly time step to 2040, to allow irrigation expansion insights and water management and planning for both the short and longer term. A novel aspect of the model is that it balances between accurate crop modeling and long-term policy assessment for irrigation expansions, by integrating a process-based crop growth model into a basin scale agricultural system dynamics model in the presence of explicit feedbacks as presented in the dynamic hypothesis in section 4.4.1. Additional supporting information for the structure and development is available in section D2 of the supplementary material of Chapter 4 (Appendix D) as well as Appendix A.

4.4.2.1 Process-based crop growth component

A process-based crop growth model is at the core of AISS. The crop growth component adopts the calculation procedures and algorithms of the FAO's AquaCrop model (Steduto et al., 2009). The model is based on a water-driven growth engine that expresses the relationship between crop biomass and transpiration using water productivity constant, WP (Steduto et al., 2012). Water-driven crop models generally perform better and are more suitable for irrigation and water use assessments than carbon- or radiation-driven models (van Ittersum et al., 2003). The effects of CO_2 concentrations on crop yields is simulated according to Raes et al. (2009) by adjusting the WP parameter.

4.4.2.2 Water demand, supply, and management component

AISS simulates the soil water dynamics on a weekly basis at a field scale. The net irrigation water demands are calculated based on the actual water transpired by the crops and the evaporation from the soil. In aggregating the water demands to the basin level, the on-farm irrigation water demands use the application efficiency of the irrigation sector, as presented in section 4.4.2.3. Further, the gross water demands at the headworks are derived by dividing the on-farm irrigation demands by the total efficiency of the conveyance infrastructure. This total gross irrigation demand is then compared with the available water supply to determine the weekly water withdrawal. The withdrawn water is then used to satisfy the irrigation demands.

Under conditions of adequate supply, each field receives exactly what it requires. When demands cannot be fully satisfied, the model allocates the available water first to higher value crops (fields), as calculated in the economic subcomponent of the model (described in section 4.4.2.4). Consequently, water stresses can affect the crop growth and reduce the end-of-season yield. This represents one of the major feedback loops described in the "*Water shortage*" loop (Figure 4.4). Simulated streamflow obtained from the hydrologic model is used as the weekly supply to the storage component of the model. AISS models the reservoirs as a stock that tracks the changes between the outflows and the inflows over the length of the growing season. Withdrawal is based on the irrigation demands on a weekly basis. The maximum allowable cumulative withdrawal is based on the total water license allocation for the irrigation sector, regardless of the available water supply.

4.4.2.3 Irrigation infrastructure and application technology component

The model calculates the on-farm irrigation water requirements based on the irrigation application efficiencies of four application methods: low pressure center pivots, high pressure center pivots, wheel move systems, and gravity. Efficiency values were obtained from AAF (2016). Further, to account for future technologies that could emerge, the model adds a fifth irrigation method called "new technology". Based on the irrigation application technology, the model estimates the water pumping time for each irrigation event, and thus quantifies the changes in irrigation technology in terms of the cost of production, as represented in section 4.4.2.4. Further, the model derives the total gross irrigation water demand at the headworks from the on-farm requirement, after accounting for water losses through the conveyance infrastructure (seepage and evaporation). The model incorporates three common conveyance systems: unrehabilitated earth canals, lined canals, and pipelines. Alberta has a total of 7,932 km of conveyance works, of which about 3,900 km are in pipelines (AAF, 2017), and plans to further reduce conveyance losses by replacing open channels with pipelines to reach 5,925 km by 2035.

4.4.2.4 Agricultural production economics

Net returns from the irrigation sector are calculated as the profit margin, calculated from the value of production and the total direct expenses. To calculate the expenses, the model divides each expense into non-water costs and water costs. Non-water production costs were obtained from various sources including the AgriProfit$ annual reports (Government of Alberta, n.d.), Alberta's CropChoice$ software, and the Crop Budget Calculator of Alberta. Water costs in the model are based on the amount of water pumped into the fields. The model simulates the changes in the energy required to pump for water delivery based on the actual amount of irrigation water requirements at the farm gate, as calculated in the crop growth component. Energy costs reflect the fractions of electricity and natural gas-based pumping systems in Alberta. Pumping hours are calculated from the pivot size, pivot flow rates, overall pump efficiency, and the pump operating pressure.

4.4.2.5 Socioeconomic responses

Socioeconomic responses of the irrigation sector are represented dynamically and endogenously in the model. We employ rating scales as proxies to represent irrigators' attitudes to risk, based on economic, social, and environmental sources. This permits quantification of the factors that influence the rate of adoption of the improved irrigation technologies and irrigation expansion in Alberta (for discussions of factors see Bjornlund et al., 2009; Nicol et al., 2010; Wang et al., 2016, 2015; Wheeler et al., 2013).

Rating scales have been used as tools to measure quantitatively a social factor that is difficult to evaluate directly (Greiner et al., 2009; Lagerkvist, 2005; Maart-Noelck and Musshoff, 2014; Sulewski and Kłoczko-Gajewska, 2014). They are typically derived from survey data or interviews with a targeted group, such as irrigators in this study, and convey their attitudes toward the statement or the question under consideration (Bard and Barry, 2000). Here, we used the concept of rating scales to describe social components that would otherwise be either represented as external variables or ignored. Following Bard and Barry (2000), we used a Likert scale score to describe two main decisions that irrigators often encounter: 1) the decision to expand the irrigated land area, and 2) the decision to upgrade existing irrigation application methods to more efficient technologies.

The decision to expand irrigated areas is driven by three factors described in the model as indicators: water demand risk (endogenous, or calculated by the model), irrigation productivity (endogenous), and aridity index (exogenous, or external variable not affected by the model results). Four indicators drive the decision to adopt improved irrigation technologies: relative incentives (exogenous), relative extension services (exogenous), irrigation productivity (endogenous), and water demand risk (endogenous). The dynamic hypothesis behind the decision scores are shown in Figure 4.5.

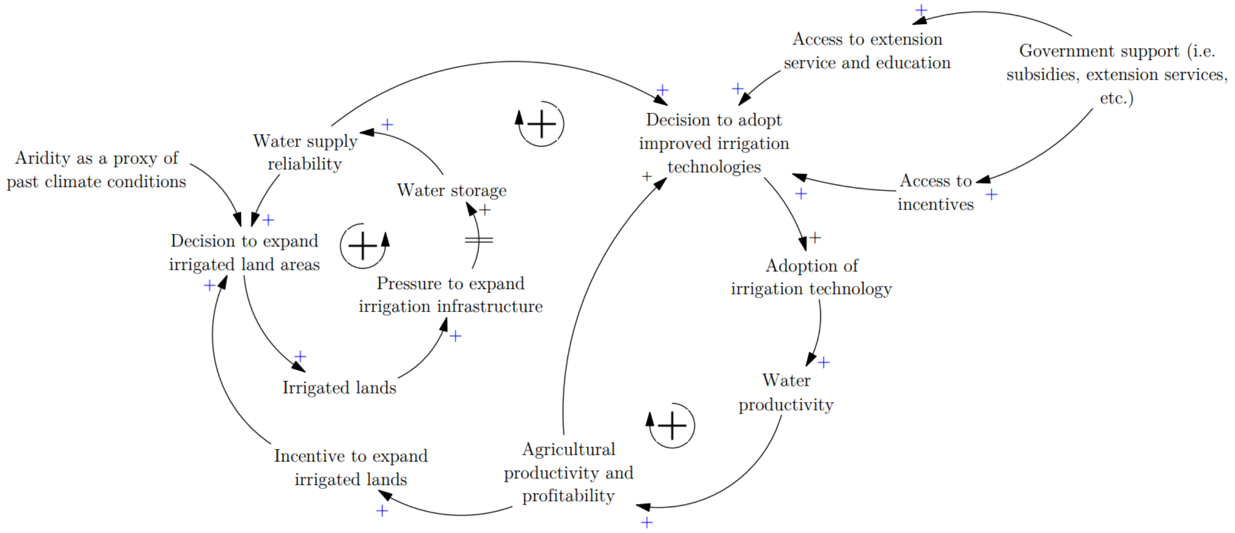

Figure 4.5. The socioeconomic factors dictating the decisions of the irrigation sector to adopt improved irrigation application methods and to expand the irrigated land areas

We applied a score range for each index ranging between the minimum and maximum values shown in Table 4.1. A logistic response function is described for each index to represent a corresponding score with different values for the index (Figure 4.6). Two of the five indices are relative to past conditions, namely the score of the extension service and the score of the incentives. Relative extension service is defined as the number of visits of extension services to the farmer in the future divided by the number in the past. Similarly, the relative incentive is the current incentives provided divided by the past government incentives. The water demand risk is the ratio of water withdrawal to water license from the previous year in the simulation. The irrigation productivity index is defined as the ratio between crop yield of an irrigated land unit and the corresponding dryland yield of the year prior to the current simulation year. Finally, the aridity index is the ratio between the seasonal precipitation to the seasonal evapotranspiration of the growing season prior the season of simulation.

In the absence of formal survey data or interviews to derive the score range and weight for each indicator, we have assumed that each indicator contributes equally to the final decision scores. Further, the historical reference values for the indices are set to 1. To understand the principle of the approach, assume that the historical productivity of irrigation is twice that of dryland agriculture. Then the value 2 is chosen as the reference index value and corresponds to a reference productivity score of 1. Reference values for the indices are shown in Table 4.1.

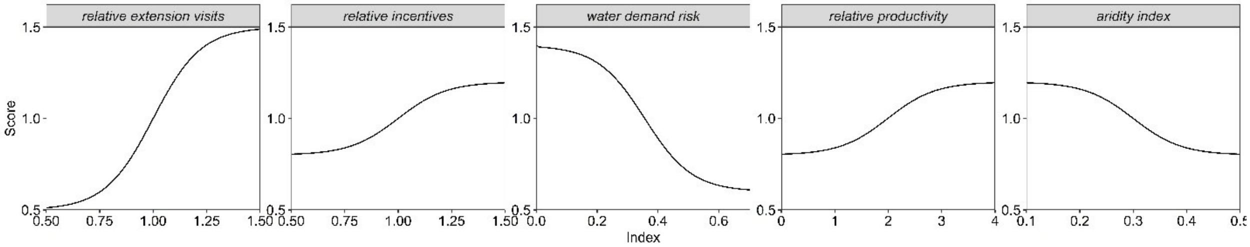

Figure 4.6. Response curves for the five indicators that describe the social decisions by the irrigation sector of southern Alberta to adopt improved irrigation application technologies and expand irrigated land areas

Table 4.1. Criteria for the factors that determine the decision score for the irrigation technology adoption

Causality	**Range** "*Variable ranges from…*"	**Ref.**	**Score** **Min.**	 **Max.**
Extension services	0 to 2	1	0.5	1.5
Government Incentives/Access to funds	0 to 2	1	0.8	1.2
Water demand risk	0 to 1	0.35	0.6	1.4
Irrigation productivity	0 to 4	2	0.8	1.2
Aridity index	0 to ∞	0.3	0.8	1.2

*Ref: reference index value denotes the index value that corresponds to a decision score of 1. References values are derived from the historical period 2006-2015.

Based on the simulations, the overall decision score changes the rate of expansion of the irrigation area, which affects the growth of the irrigated area directly, through the following equation:

$$\frac{dI}{dt} = \left(\theta_{exp} \cdot r_{base}\right) \tag{4.1}$$

where dI/dt is the rate of expansion in the irrigated area (ha yr^{-1}), θ_{exp} is the decision score to expand the irrigated land areas represented as a multiplier simulated endogenously, r_{base} is the base expansion rate (fraction yr^{-1}).

4.4.3 Model performance, assessment, and validation

The structural validity of the system dynamics model was assessed based on two steps: (1) validation of the process-based crop growth model, and (2) validation and performance testing for the integrated system dynamics model.

We ensured first that our adaptation of AquaCrop model in a system dynamics framework implemented the mathematical equations correctly during the migration process of AquaCrop to system dynamics. We tested the process-based crop growth component by simulating barley, maize, and potato production on three hypothetical farms in three different regions (i.e., Canada, US, and Belgium). The tests compared the crop yield and the soil water content estimations with values from AquaCrop for the same datasets. Crop yields showed R^2 of 0.95, 0.98, and 0.92 for barley, maize, and potato simulations, respectively (Ammar and Davies, under review). The behavior of AquaCrop in simulating the various processes was reproduced correctly, and the structure of the model was validated.

Next, the model was validated with real observations for the crop yield for the six simulated crops using three statistical measures: coefficient of determination (R^2) to explain the magnitude of the model variance compared to the total observed variance, normalized root mean square error (RMSE) to measure how good the predictive crop model is compared to the observed data, and the mean bias error (MBE) to indicate over/underestimation of the model. Observation data were obtained from the Agriculture Financial Services Corporation (AFSC, personal communication) and from its annual "Alberta Yields" reports for the irrigation districts. Data were extracted for the growing seasons of 2006 to 2012 for the entire irrigation areas and aggregated into basin-scale values. Crop parameters were modified based on AquaCrop's default crop files, which contains both site-specific and constant parameters. Site-specific parameters were set to local conditions based on calibration by Langhorn (2015) for barley, canola, and wheat, and values were modified after Casa et al. (2013) and Stricevic et al. (2011) for potatoes and sugar beets, respectively. While AquaCrop does not support the simulation of alfalfa, we followed Kim and Kaluarachchi (2015) to create a crop parameter file for leafy crops that mimic the growth of alfalfa, with appropriate modifications to durations of growth stages to match growth conditions in Alberta, obtained from AAF (2011) and (Attram et al., 2016) and compared with values reported in the literature (Allen et al., 1998a; Sulc et al., 1999). All crop input parameters are summarized in the supplementary material section 4.4.

The seasonal variability in crop yields was adequately captured by values for R^2 of 0.72 for alfalfa, 0.90 for barley, 0.50 for canola, 0.67 for potatoes, 0.74 for sugar beets, and 0.76 for wheat. We used one set of crop parameters to represent the entire basin, since the primary objective was to capture the spatial heterogeneity in yields. There was good agreement between simulations and observations in this respect over the evaluation period of 2006-2016 (Figure 4.7). Note that the model does not capture the effects of extreme climate conditions, diseases, pests, or crop damage from hail.

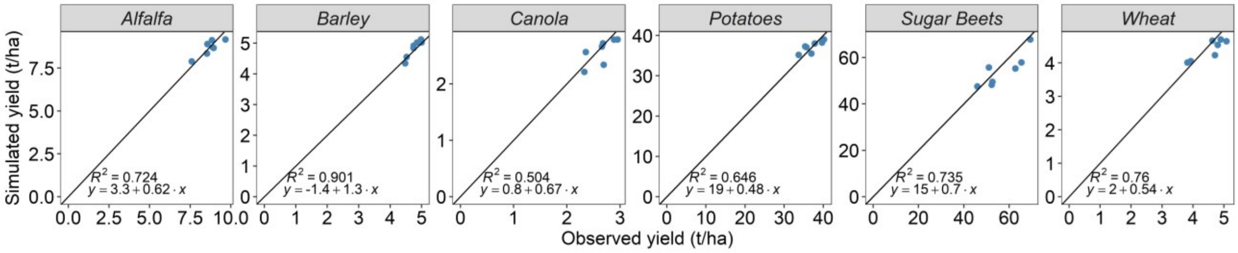

Figure 4.7. Statistical measure and validation of the process-based crop growth component of AISS

The second step involved testing and evaluating the performance of the system dynamics model. SD models are used to provide insights on system behavior or trends over time rather than for prediction of exact single values. A number of standard validation tests are available (Barlas, 1996, 1994; Mirchi et al., 2012; Sterman, 2000) for validating the structure of a SD model, including (1) boundary adequacy, to ensure that all of the critical processes are included endogenously to serve the model's intended use or purpose adequately; (2) dimensional analysis, to examine the consistency of the mathematical equations used to build the model; (3) model parameters validation, to ensure that the model describes real-world systems; (4) extreme conditions test, to ensure that the model does not respond irrationally when given extreme inputs; and (5) behavior reproduction tests, to ensure that the model replicates historical trends under the same conditions.

Boundary adequacy was verified based on literature, expert opinions from the workshop with stakeholders (Ammar et al., 2014), and exposure in conference presentations. In the dimensional analysis test, the left and right sides of each equation of the model were verified to be of the same units. The test was successful and confirmed that the model structure is consistent, and the equations adequately represent the corresponding processes in the real world. Model structure and parameters validation were based on using the state-of-art crop modeling approaches from existing well-established crop growth models as described in section 4.4.2.1, and the parameters were established using existing literature, government documents and reports, and calibrated data to set model parameters, including, for example, crop growth parameters, crop mix ratios, operating pressures and efficiencies for irrigation pivots and wheelmove systems, and crop production costs. Extreme conditions tests evaluated model response to extreme input changes. Three extreme tests of no water supply, no rainfall and no water supply, and full water supply were simulated to check the model's simulated behavior against the anticipated real behavior for soil water content, accumulated crop biomass, pumping costs, and live water storage (see supporting information in the supplementary material section 3). Finally, model behavior was validated through the reproduction of historical trends. The total seasonal irrigation water withdrawal at the headworks in billion cubic meters was used for comparison from 2006 to 2016 with historic withdrawal (Figure 4.8). Weekly generated results by the model were aggregated into annual values that were then compared against annually reported diversions by Alberta Agriculture and Forestry (AAF, 2017) after deductions of changes in reservoir storage levels. These comparisons yielded an R^2 of 0.8436, RMSE of 0.134 bcm (billion cubic meters), and Mean Bias Error (MBE) of 0.015 bcm.

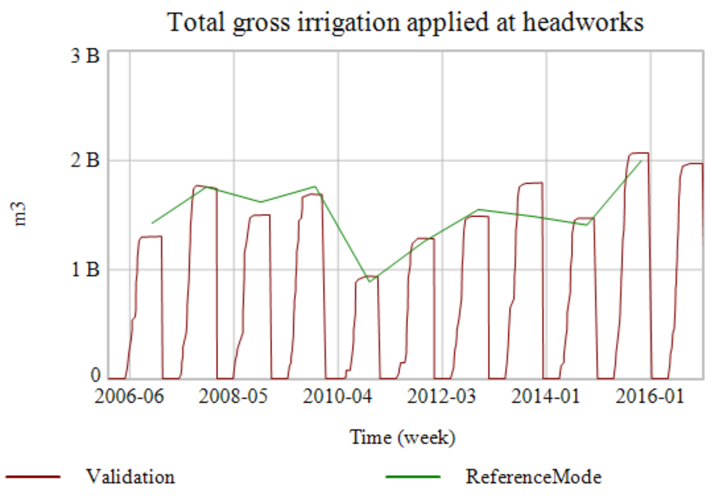

Figure 4.8. Comparison of the simulated total gross irrigation water withdrawal for 2006-2016

4.5 Model Application

4.5.1 Scenario-based analysis and modeling

Future changes in agricultural production and water demands of the irrigation sector of southern Alberta are assessed through a scenario-based approach. Fourteen scenarios in six groups were generated to explore a range of plausible futures for the irrigation sector and to assess its capacity to changes in the irrigated land area, crop mix ratios, future climate, and adaptation policy interventions.

4.5.1.1 Irrigation expansion scenarios

Four irrigation expansion scenarios provide a range of expansion levels, and are called business as planned (BAP), stagnation (ST), slow development (SD), and rapid development (RD) – see Table 4.2. In the first scenario (BAP), the expansion rate is based on a goal set by the Government of Alberta (2017) to reach 625,000 hectares (+8% from current irrigation land area) by 2025. The stagnation scenario assumes the irrigated area remains unchanged from 2017 onwards. In the slow development scenario, the expansion goal of 625,000 is reached by 2040. Finally, the rapid development scenario uses an expansion rate that begins with the BAP scenario rate, but then continues to 2040 for a total increase of 22% from the existing irrigated land base.

Table 4.2. Irrigated land area expansion scenarios

Scenario [a]	**Irrigated land area**
BAP	+8% by 2025
ST	No change
SD	+8% by 2040
RD	+22% by 2040

4.5.1.2 Crop mix change scenarios

A second set of four scenarios reflect a range of possible alternatives for the crop mix, as presented in Table 4.3. Alberta has had a relatively stable crop mix since 2014 (AAF, 2017). In the first scenario ($\mathrm{CM_{CC}}$), current crop mix is assumed to continue to 2040 – neither government reports nor the workshop provided information on a planned long-term crop mix. $\mathrm{CM_{WI}}$ assumes a substantial increase in alfalfa over the course of the simulation to reflect a water-intensive crop mix. A moderate water consumptive crop mix is assumed for third scenario ($\mathrm{CM_{WC}}$) with a considerable decrease in alfalfa and increase to barley and canola crops as compared to the current crop pattern. Finally, in high-value crop mix ($\mathrm{CC_{HV}}$), high-value crops are increased 100% by 2040 for both potatoes and sugar beets with a substantial decrease in alfalfa – See Table 4.3.

Table 4.3. Crop mix scenarios

	Crop mix scenario	**Alfalfa**	**Barley**	**Canola**	**Potatoes**	**Sugar beets**	**Wheat**
$\mathbf{CM_{CC}}$	Current crop mix (reference)	0.23	0.17	0.19	0.05	0.03	0.33
$\mathbf{CM_{WI}}$	Water intensive crop mix	+52%	-41%	-37%	0%	0%	+6%
$\mathbf{CM_{WC}}$	Water conservative crop mix	-48%	+59%	+32%	0%	0%	-15%
$\mathbf{CM_{HV}}$	High value crops	-57%	-47%	+58%	+100%	+100%	+6%

4.5.1.3 Policy sets and adaptation measures

This group of scenarios assesses several policy interventions for their effects on the irrigation sector of Alberta. During the past decade, the province has relied on infrastructure enhancements to allow expansion of the irrigated area with no added risk to irrigators. Four policy sets based on five adaptation measures were developed to explore a wide range of alternatives. The policy sets range from no adaptation measures to the maximum capacity for water conservation – see Table 4.4 for details on policy sets. The five adaptation measures include incentives and subsidies, extension services, irrigation application and conveyance efficiencies as modeled according to section 4.4.2.3, and the total live storage. Policy interventions are applied from 2017 onwards. Finally, the two climate scenarios of RCP 2.6 and RCP 8.5 were assessed as well.

Table 4.4. Policy sets and the corresponding adaptation measures

Policy set	**Policy intention:** *"Represents…"*	**Incentives**	**Extension services**	**Irrigation Technology**	**Conveyance Infrastructure**	**Storage**
PS$_{BAP}$	As planned adaptation	No change	No change	Target efficiency to reach 85% by 2025	Pipelines to reach 5,925 km by 2035	+5%
PS$_{DC}$	Unconcerned policy direction; DC refers to "Don't Care." (reference)	No change	No change	Efficiency at the current level	No change Pipelines at 4100 km	No change
PS$_{MA}$	Moderate adaptation strategy	Higher	+20%	Efficiency to reach 90% by 2040	Pipelines to reach 5,925 km by 2040	+5%
PS$_{HA}$	High adaption strategy	Higher	+40%	Efficiency to reach 95% by 2040	Pipelines to reach 7,593 km by 2040	+10%

4.6 Results and discussion

4.6.1 Scenario combinations

Scenario planning and development was a key step for AISS to generate meaningful quantitative results. In this study, 128 possible combinations were derived from the four irrigation expansion scenarios, the four crop mix scenarios, the four policy sets, and the two climate change scenarios described in section 4.5.1. The combinations were assessed against their ability to represent plausible future conditions and chosen such that they cover a representative range for the irrigation sector in the future. For instance, a combination of rapid expansion scenario (RD) with high-value crop mix (CM_{HV}) and the highest level of policy interventions (PS_{HA}) would answer, "*What does the irrigation sector look like in 2040 with high-value crops and the implementation of the highest policy interventions?*" Here, we selected 14 scenario combinations under six scenario groups beside the base case scenario – see Table 4.5. Each scenario group represents a particular theme and poses a central question to answer, while combinations of scenarios permit exploration of the irrigation sector in the form of "*what-if*" questions, to identify places of management leverage or potential, and possible tipping points. The tested scenario groups are summarized as follows:

- Base Case (BC): Generated using the current state of the irrigation sector and serves as the basis of comparison for other scenario groups. It establishes a baseline time series that was simulated without changes in the irrigated land areas, crop mix ratios, no adaptation measures.
- Scenario group 1 (S1): Focuses on impacts of climate change on both crop yields and water demands – these are the most commonly assessed variables in agricultural studies. The two climate change scenarios (RCPs) were simulated for each of the five members of the ensemble, no adaptation measures were adopted, and the irrigated land area remained unchanged at 578,125 hectares. The irrigation application technology fractions were fixed at their current values of 75%, 8%, 9%, and 8% for low-pressure center pivots, high-pressure center pivots, wheel move, and gravity systems, respectively. This scenario group tests the capacity of the irrigated

sector under the existing structural and physical features, socioeconomic factors, and irrigators' responses to climate change. The storage capacity of the irrigation sector will also remain unchanged at a total value of 2.931 bcm. Note that we set the water supply to a high value, so that the model does not activate the "*Water shortage*" (-) feedback loop in Figure 4.4.

- Scenario group 2 (S2) defines two extreme scenarios for the irrigation sector that would provide the lowest and the highest irrigation demands: the first scenario (ST_CM$_{WC}$_85_PS$_{HA}$) assumes no change in the land area, conversion to a water conservative crop mix by 2040, and a high adaption policy set. The second scenario (RD_CM$_{WI}$_85_PS$_{DC}$) assumes a continuous irrigation expansion beyond the planned expansion limit of 625,000 hectares to reach 703,000 hectares by 2040 (i.e., an increase of 22% to the base case). Further, the "Don't Care" policy set was used with a water-intensive crop mix. The aim of this scenario group is to provide a wide envelope of demand changes for the future of the irrigation sector under unlimited water supplies, as assumed in S1.
- Scenario group 3 (S3) includes three different area expansion rates, future climate and unlimited water supply conditions, and planned policy interventions as defined by the Government of Alberta (2017) in its irrigation expansion strategy for the future. The first scenario of the group adopts the planned rate (BAP_CM$_{CC}$_85_PS$_{DC}$) to reach an expansion limit 625,000 ha by 2025 and then no expansion occurs after that point. The second (SD_CM$_{CC}$_85_PS$_{DC}$) and the third (RD_CM$_{CC}$_85_PS$_{DC}$) scenarios assume slow and rapid expansions, respectively, according to section 4.5.1.1. The three scenarios all adopt the current crop mix conditions. This group aimed at comparing the changes in the irrigation demands in response to only changing the irrigation land areas

- Scenario group 4 (S4) focuses on changes in the cropping pattern, using four scenarios that change only the crop mix ratios. The four crop mix ratios are the current mix ($ST\_CC_{CC}\_85\_PS_{DC}$), water intensive crop mix ($ST\_CC_{WI}\_85\_PS_{DC}$), water conservative crop mix ($ST\_CC_{WC}\_85\_PS_{DC}$), high-value crop mix ($ST\_CC_{HV}\_85\_PS_{DC}$). While the water conservative and water intensive crop mix scenarios do not necessarily represent the cropping trends in Alberta's irrigation, they generate the maximum and the minimum crop water use, and gross demands to compare against the base case scenario.
- Scenario group 5 (S5) explores the effects of the different policy interventions. Three scenarios with three different policy sets establish the group. The first policy includes the "business as planned" adaptation measures ($ST\_CM_{CC}\_85\_PS_{BAP}$), where the model simulates the irrigation sector in response to changes in irrigation application technology, conveyance system infrastructure, reservoir storage, extension services, and government incentives. The two other scenarios incorporate the "moderate adaption" ($ST\_CM_{CC}\_85\_PS_{MA}$) and "high adaptation" ($ST\_CM_{CC}\_85\_PS_{HA}$) policy sets, respectively. No other model variables were altered, including area expansion scenarios and crop mix ratios. It should be noted that the scenario group is tested under the rapid development expansion scenario. This scenario is likely to generate the highest water demand, and thus impacts of the interventions will be more observable.
- Scenario group 6 (S6) combines scenarios to study the joint impacts of different land expansion rates, crop mix ratios and policy interventions, compounded with future climate conditions and water supplies using the ensemble mean of the five climate models. In short, S6 provides plausible scenarios for policymakers, or water managers, to imagine how the future for the irrigation sector might unfold. This

scenario group tests the adapt capacity of the planned changes in the irrigation infrastructure and policy measures to different expansion rates. Further, it provides insight into whether decision makers continue expanding with the same rate beyond the 2025 expansion limits under the same policy interventions or others might be worthwhile.

To evaluate the potential impacts of the various scenario groups on crop production, total gross irrigation water demands, and irrigation economic returns, scenario groups 1 to 5 assumed an unlimited water supply to the irrigation districts. In scenario group 6, the model used the ensemble-mean water supply from the hydrologic model to allow for possible water shortage feedbacks in the model. In S6, the impacts of the limited water supply were compared against corresponding cases with full water supply in order to show the significance of feedback loops that altered the model behavior.

Table 4.5. Scenario groups and associated changes to the AISS model scenario setup used to explore the irrigation sector of southern Alberta

Scenario groups and combinations [a]		**Scenario group theme**	**Scenario question**
Group ID	Scenarios		
BC	ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{DC}}$	Reference simulation	
S1	ST_ 26 ST_ 85	Changes in future climate	What are the impacts of a low and high CO$_2$ emission climate change scenario on future crop yields and irrigation demands?
S2	ST_CM$_{\mathrm{WC}}$_85_PS$_{\mathrm{HA}}$ RD_CM$_{\mathrm{WI}}$_85_PS$_{\mathrm{DC}}$	Lowest and highest irrigation demands	What are the boundaries of water demand and economic returns for Alberta's irrigation sector?
S3	BAP_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{DC}}$ SD_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{DC}}$ RD_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{DC}}$	Changes in irrigation expansion rates	What are the impacts of changing only the irrigation expansion rates on water demands and economic returns?
S4	ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{DC}}$ ST_CM$_{\mathrm{WI}}$_85_ PS$_{\mathrm{DC}}$ ST_CM$_{\mathrm{WC}}$_85_PS$_{\mathrm{DC}}$ ST_CM$_{\mathrm{HV}}$_85_PS$_{\mathrm{DC}}$	Changes in crop mix ratios	What are the impacts of changing only the crop mix ratios on water demands and economic returns?

S5	ST_CM$_{CC}$_85_PS$_{BAP}$ ST_CM$_{CC}$_85_PS$_{MA}$ ST_CM$_{CC}$_85_PS$_{HA}$	Changes in policy interventions	What are the impacts of changing only the adaptation policies on water demands and economic returns?
S6	BAP_CM$_{CC}$_85_ PS$_{BAP}$ BAP_CM$_{CC}$_85_PS$_{HA}$ RD_CM$_{WI}$_85_PS$_{DC}$ RD_CM$_{HV}$_85_PS$_{HA}$	Changes in crop mix and adaptation strategies for "business as planned" expansion scenario	What does the irrigation sector in southern Alberta look like in 2040 based on each scenario?

[a] Scenario name abbreviations: BAP = business as planned, ST = stagnation, SD = slow development, and RD = rapid development; CC$_{CC}$ = current crop mix, CC$_{WI}$ = water intensive crop mix, CC$_{WC}$ = water conservative crop mix, CC$_{HV}$ = high value crop mix; 26 and 86 refers to the CO_2 concentrations scenarios of RCP 2.6 and RCP 8.5, respectively; and PS$_{DC}$ = "Don't Care" policy set, PS$_{BAP}$ = business as planned policy set, PS$_{MA}$ = moderate adaptation policy set, and PS$_{HA}$ = high adaptation policy set.

4.6.2 Scenarios assessment indices

A main interest for the case study is the impacts of climate change on crop yields of the major six crops of the irrigation districts; therefore, the future crop yields were simulated, and their trends were analyzed. Changes in total gross irrigation water demand, total agricultural economic returns, and total water profitability (economic returns ($) per a unit of water diversion (m^3)) were estimated every five years from 2016 to 2040. In addition, the performance of each scenario combination was assessed against four indices over the simulation period from 2006 to 2040. The indices as follows:

- Water productivity index (WPI, t m^{-3}): total crop production divided by the volume of irrigation water diversions at headworks. It provides a measure of productive output per unit of irrigation water diverted;
- Water economic index (WEI: $ m^{-3}): total irrigation income divided by the total irrigation water diversions at the headworks;
- Land economic index (LEI, $ ha^{-1}): the total economic return divided by the total area irrigated land area; and,
- Profitability index (PT, $ t^{-1}): the total irrigation returns divided by the total crop production.

Further, the percentage changes in the crop yields for the six representative crops under the two climate scenarios were estimated to study the impacts of climate change on crop production. Percentage changes of the gross irrigation demands at the headworks were also computed.

4.6.3 Scenario groups and combinations modeling

4.6.3.1 Reference simulation: Base case scenario

The base case scenario ($ST\_CM_{CC}\_85\_PS_{DC}$) provides a benchmark time series for comparison against all the subsequent scenarios. Results presented in Figure 4.9 show the variability of the irrigated land base, the total irrigation water demands in billion m^3, and the total contribution margin (revenue minus variable costs) for the simulation period from 2006 to 2040 using the ensemble mean climate model under RCP 8.5.

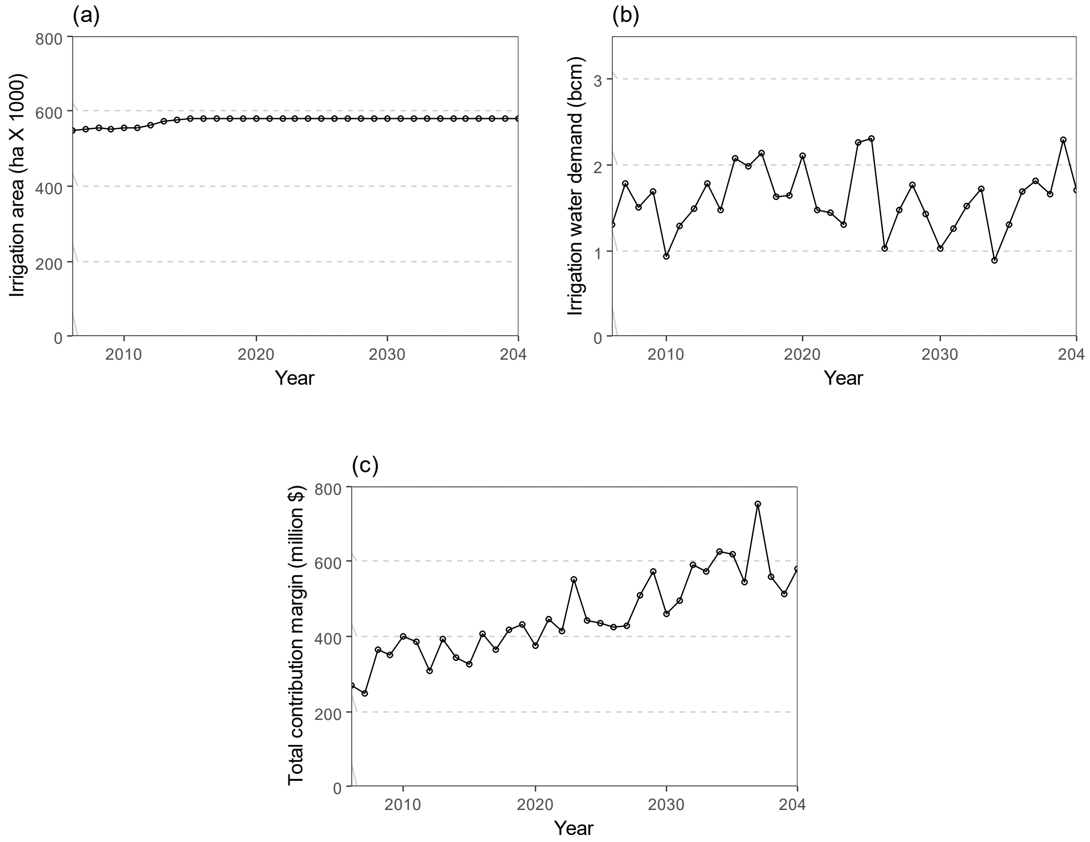

Figure 4.9. Reference simulation results for the irrigation area (a), total irrigation water demands (b), and total contribution margin (c)

4.6.3.2 Projected changes to future crop yields

In scenario group 1, the model simulated a continuous increase in the dry matter crop yields for the six irrigated crops under an ensemble of the two climate scenarios with elevated CO_2 levels – see Figure 4.10 Weather variability had a significant impact in the estimation of the crop yields, as is evident in the varying yield estimates from one season to the next based on variable seasonal temperatures and accumulated growing heat units. Simulations also showed that each crop type responded differently to climate change. Notice, for example, that sugar beets in both RCP 2.6 and RCP 8.5 were more sensitive to weather variability between years. The results showed an overall positive trend for all the six crops, and a steeper increasing growth rate in RCP 8.5 compared to RCP 2.6. There is a consensus in the literature that crop yields will increase with higher temperatures due to climate change, because of the stimulation effects of higher CO_2 in the future (Kimball, 2016; Tubiello et al., 2007; Wang et al., 2013). The increase rate differences between the two scenarios were 0.028 t yr^{-1} for alfalfa, 0.014 t yr^{-1} for barley, 0.008 t yr^{-1} for canola, 0.024 t yr^{-1} for potatoes, 0.026 t yr^{-1} for sugar beets, and 0.013 t yr^{-1} for wheat. Recall that water supply was unlimited for this scenario group to avoid crop stresses resulting from water shortage, and the simulated changes are only impacted by future climate inputs.

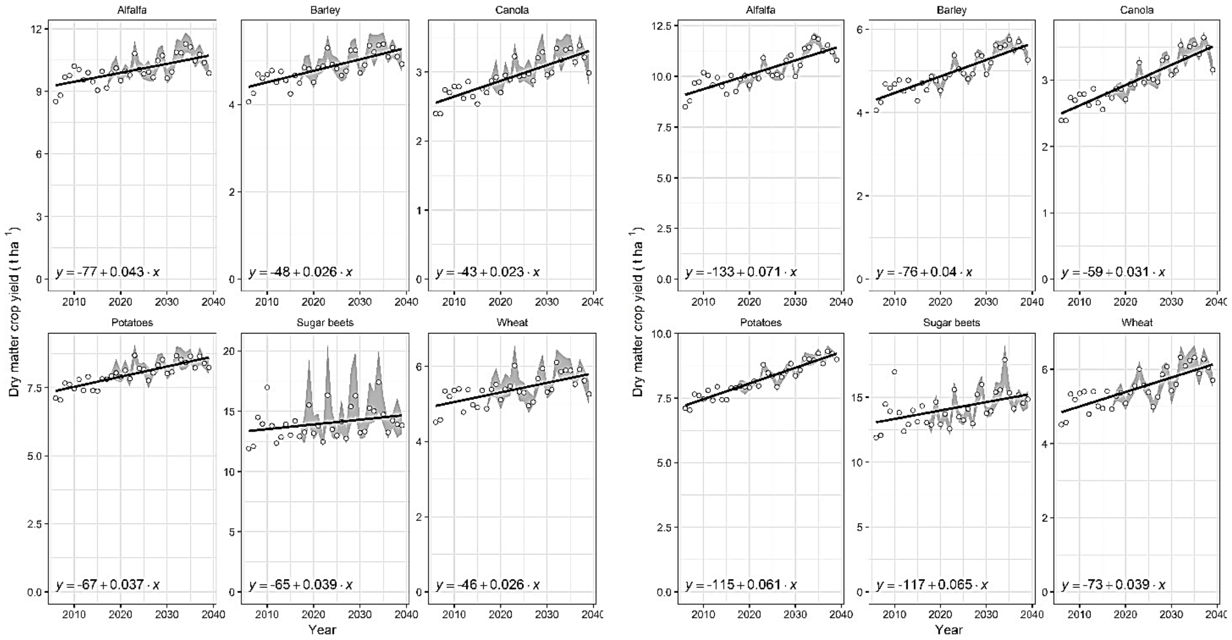
(a) (b)

Figure 4.10. Projected changes in the crop yields of the six representative crops under RCP 2.6 (a) and RCP 8.5 (b) using an ensemble of five climate models

In contrast, gross irrigation water demands did not obviously decrease or increase with climate change – see Figure 4.11. In the low emission climate scenario (RCP 2.6), the simulated water demands for the mean ensemble climate model varied between an increase of 10%, 3%, and 7% for the periods of 2016-2020, 2021-2025, and 2036-2040 compared to

2011-2015, respectively, and a decrease of 1% and 13% for 2026-2030, and 2031-2035, respectively. In contrast, the higher emission scenario (RCP 8.5) showed a larger increase of 14% for 2016-2020, 9% for 2021-2025, 3% for 2026-2030, and 11% for 2036-2040, and a lower decrease of 8% in 2031-2035 compared to RCP 2.6. These findings are in agreement with those of Islam and Gan (2015) for an increase between 2–13% in 2010–2039 in Alberta's irrigation demands.

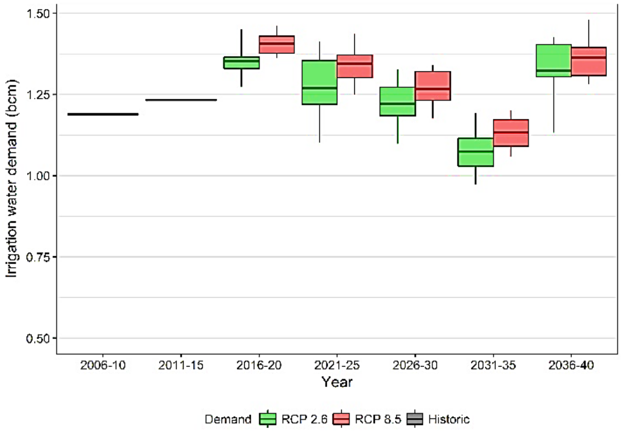

Figure 4.11. Simulated gross irrigation water demands at headworks under climate change averaged over a running 5-year period from 2006 to 2040 under RCP 2.6 (green) and RCP 8.5 (red) using an ensemble of five climate models

4.6.3.3 Projected changes to future irrigation water demand

Lower and upper boundaries of the irrigation sector

The lower and the upper boundary scenario group (S2) results for the assessment indices are shown in Figure 4.12. The variability of the climate between seasons clearly had the largest effects on the estimation of all the indices. For the water productivity index (WPI), although the upper boundary scenario (i.e., highest potential water demand) had the most water-intensive crop mix, it did not show any decrease in the total production per irrigation demand, because alfalfa has a relatively higher yield than barley and canola. In some cases, it had higher tonnage production than both barley and canola together.

The three water, land, and agronomic (profitability index) economic indices showed different behaviors. For instance, the upper boundary scenario had a smaller increase in the economic return per unit of water diverted with a maximum increase of 3.6% in the period 2036-2040 compared to the lower boundary scenario, which showed an increase of 20.5% for the same period. As for the economic returns per unit of land, the upper boundary scenario showed a gradual increase across all periods to reach 6.7% in 2036-2040 while the lower boundary showed a gradual decrease up to 6.2% in the 2036-2040 period. In contrast, the irrigation economic returns per unit production showed an overall gradual decrease for the upper boundary scenario to reach -3.5% by 2040 while an increase occurred in the lower boundary up to 4%. All three economic indices showed a statistically significant increasing trend ($p<0.05$). This can be attributed to the effects of the increased temperatures and CO_2 concentration on crop yields, as discussed in section 4.6.3.1.

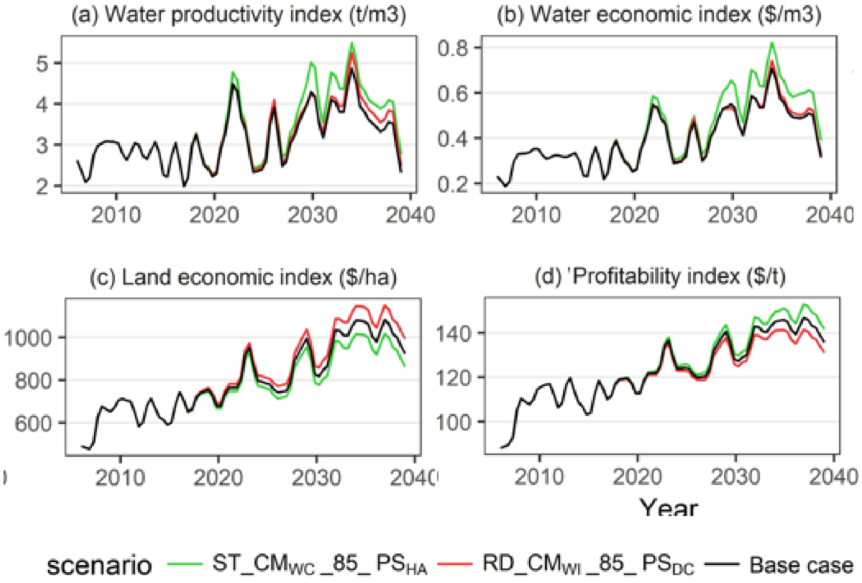

Figure 4.12. Four assessment indices for the lower and the upper boundary scenarios to define the envelope of change of the irrigation sector in terms of water productivity and water, land, and production economics. Note that the results are smoothed using a nonparametric local polynomial regression fitting (loess: see Jacoby (2000)) using a span of 0.1 for enhanced graphical presentation.

Gross irrigation water demands varied significantly between the lower boundary (ST_CM$_{WC}$_85_PS$_{HA}$) and the upper boundary (RD_CM$_{WI}$_85_PS$_{DC}$) scenarios, with a difference of 44.1% between the two scenarios as compared to the base case scenario (ST_CM$_{CC}$_85_PS$_{DC}$) by 2040. Although the lower boundary scenario had the same irrigated land area as the base case, it showed a decrease of 22.3% in the 2036-2040 period. This is due to the gradual shifts to a water conservative crop mix with less alfalfa and more barley and canola, and implementation of high adaptation interventions. Whereas the upper boundary scenario showed a gradual increase to 21.8% by the 2035-2040 period due to the continuous increase in the irrigated land area to 703,000 hectares, shifts towards alfalfa and adoption of the "Don't Care" policy. Table 4.6 summarizes the percentage change between the two scenarios for the simulation period. Effects of limited water supplies with climate change are not simulated in this scenario group. With limited supply, irrigation expansion would be interrupted and not expand at the same rate assumed; indeed, it could even completely stop. Seasonal effects of water shortages could result in crop yield reductions and an overall decrease in economic returns. Such feedback effects are critical to represent a genuine expansion scenario. We explore these effects in detail with scenario group 6, below.

Table 4.6. Percentage changes under the lower and upper boundaries (S2) for the gross irrigation demands as compared to the base case scenario

Scenario (scenario group 2)	Period						
	2006-2010	2011-2015	2016-2020	2021-2025	2026-2030	2031-2035	2036-2040
Base Case	0	0	0	0	0	0	0
Lower boundary: ST_CM$_{\text{WC}}$_85_PS$_{\text{HA}}$	0	0	-1.8%	-7.3%	-13.0%	-18.5%	-22.3%
Upper boundary: RD_CM$_{\text{WI}}$_85_PS$_{\text{DC}}$	0	0	1.8%	7.5%	13.5%	18.3%	21.8%

Ensemble scenario group comparison

The three scenario groups S3, S4, and S5 investigated the impact of individual changes in expansion rates, crop mix ratios, and policy interventions, respectively. The purpose of the ensemble of scenario groups is to compare the contribution of each of the three factors to the total change in the irrigation demands and economic returns – see Figure 4.13. For instance, scenario group 3 (S3) compared three expansion scenarios using business as planned (BAP_CM$_{\text{CC}}$_85_PS$_{\text{DC}}$), slow development (SD_CM$_{\text{CC}}$_85_PS$_{\text{DC}}$), and rapid development (RD_CM$_{\text{CC}}$_85_PS$_{\text{DC}}$); all other parameters remained unchanged from the base case scenario. RD_CM$_{\text{CC}}$_85_PS$_{\text{DC}}$ showed a gradual increase in the irrigation demands with a maximum increase of 16.6% in the 2036-2040 period. Not surprisingly, BAP_CM$_{\text{CC}}$_85_PS$_{\text{DC}}$ had higher demands for all the time periods compared to SD_CM$_{\text{CC}}$_85_PS$_{\text{DC}}$ scenario which showed an increase across all the time periods to a slightly smaller demand (~10% less) in 2036-2040 compared to the BAP expansion. Both the water and land economic indices did not reveal any changes between scenario. That result matches expectations, since there were no changes in the crop mix ratios or the management strategies compared to the base case scenario.

Interestingly, the effect on the total irrigation demands of changing crop mix ratios was not significant. A shift to more alfalfa, a 50% increase in the cultivated area, and decreases in both barley and canola areas did not produce significant increases in water demands except slight increases of 2.4% in 2026-2030 and 2.7% in 2031-2035, and then a smaller increase for 2036-2040 by 1.5%. Both the water conservative ($ST\_CM_{WC}\_85\_PS_{DC}$) and high value ($ST\_CM_{HV}\_85\_PS_{DC}$) cropping patterns showed an overall decrease in all time periods of the simulations. The percentage change in water demand for the water conservative crop mix scenario reached a maximum value of -1.0% in 2026-2030 and -2.3% in 2031-2035 period. These results suggest that changing the crop mix has low, almost negligible, impacts on the future water demands of Alberta's irrigation sector. In contrast, the different crop mix ratio simulations generated remarkable changes to both the water and land economic returns over the course of the simulation period. The high value crop mix scenario ($ST\_CM_{HV}\_85\_PS_{DC}$) generated an increase of approximately 28%, and 29% in the economic returns per unit land and unit water demand for 2036-2040, respectively, while the water conserving crop mix ($ST\_CM_{WC}\_85\_PS_{DC}$) produced an overall decrease up to 7% for LEI and 6% for WEI.

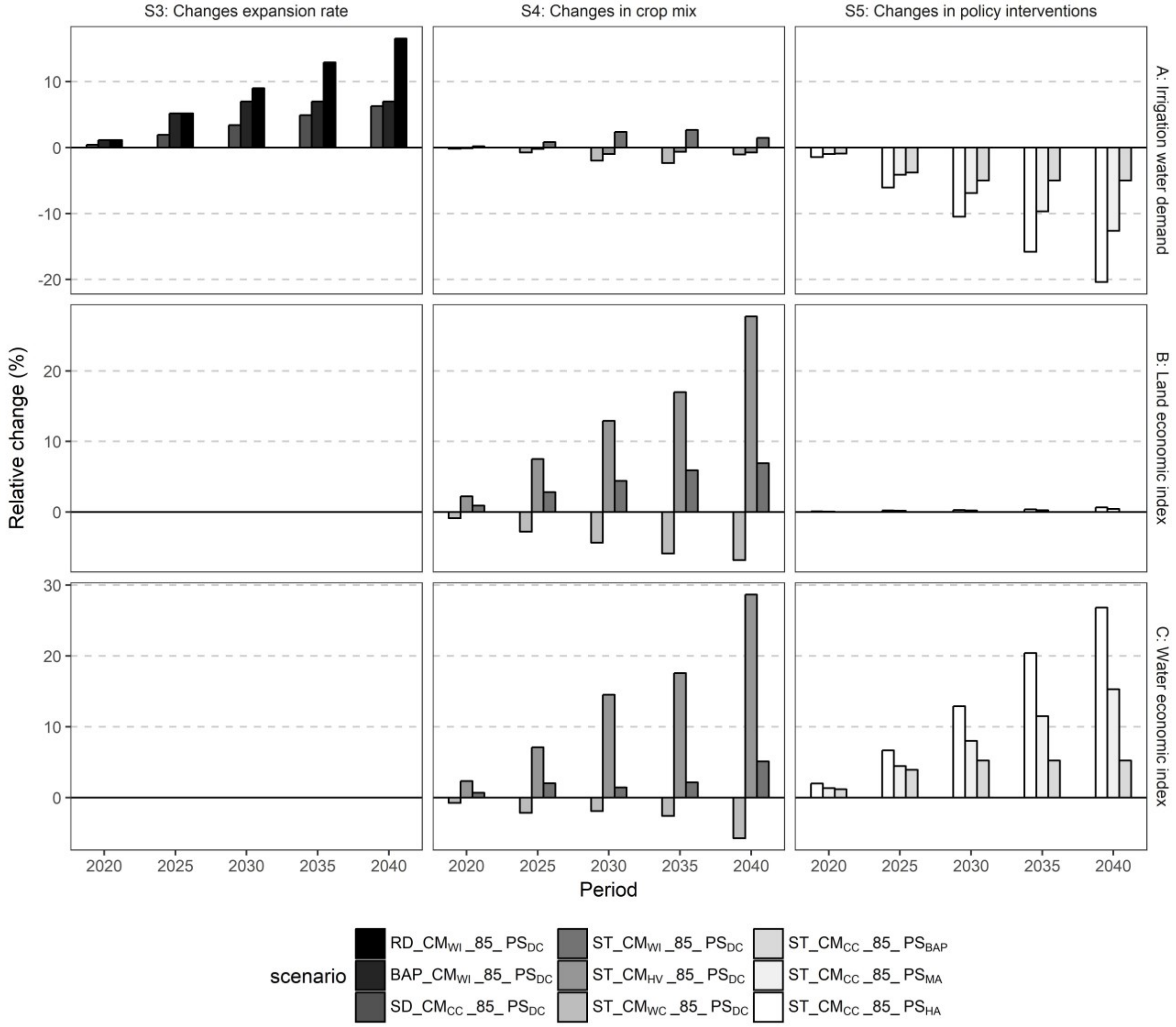

Figure 4.13. Percentage changes across the three scenario groups S3: irrigation expansions, S4: crop mix ratios, and S5: policy sets in the irrigation water demand (A), land economic index (B), and water economic index (C) as compared to the base case scenario

In comparing the impacts of the policy interventions, all the policy sets decreased the total irrigation water demands at the headworks with values ranging from 5% to 20% in the 2036-2040 period for the planned interventions and the high adaptation strategy, respectively, as shown in Figure 4.13. Surprisingly, the moderate adaptation policy set (ST_CM$_{CC}$_85_PS$_{MA}$) generated consistently lower irrigation demands than the planned policy set by the Government of Alberta (2017) (ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{BAP}}$) for all the time periods. The planned policy set assumed irrigation efficiency to reach 85% by 2025, whereas the moderate adaptation assumed an increase to 90% by the year 2040. However, the feedback effects of the decision to adopt irrigation technologies resulting from increased incentives and extension service visits resulted in a higher adoption rate and the target efficiency was reached 5 years earlier, while the rate of adoption in ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{BAP}}$ was slower and the target efficiency was reached after 2025. This slower attainment of the target resulted from model feedbacks: irrigators perceived greater water insecurity and a lower ratio between the productivity of irrigation to drylands, as described in section 4.4.2.5. These feedbacks altered the model behavior in response to the perception of water availability and the total production of irrigation. Finally, the different policy sets had marginal effects on the land economic index, with almost no change from the base case scenario. In contrast, economic gains with respect to the amount of water required were considerably higher, with a gradual increase to 5.3% for ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{BAP}}$, 15% for ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{MA}}$, and 27% for ST_CM$_{\mathrm{CC}}$_85_PS$_{\mathrm{HA}}$ by 2036-2040.

The simulations showed that a careful selection of policy interventions offset increases in demands due to expansion, even beyond the planned expansion target. Crop mix changes did not yield significant water savings but provided high economic returns both in terms of land and water.

4.6.3.4 Impacts of model feedback structure: projected changed to future irrigation water withdrawal

The last scenario group (S6) was simulated under actual water supply conditions using the ensemble climate model supply. The "business as planned" expansion scenario with the planned management strategies (BAP_CM$_{\mathrm{CC}}$_85_ PS$_{\mathrm{BAP}}$) resulted in an increase of 1.2%

in the total irrigation withdrawals over the period 2016 to 2035, and a relatively high increase of 4.7% in 2036-2040 compared to the base case scenario. The WEI increased gradually to the year 2035 to reach a percentage change of +5.2%; however, the increase slowed in 2036-2040 resulting in only an increase of 1.3% compared to the BC scenario. The LEI remained unchanged from the BC scenario except for the last period of simulation, with a percentage change of +1.1%. Further, while the land productivity in tons of crop yield per unit irrigated area was expected to remain unchanged as the crop mix did not change, the scenario showed a marginal, but unexpected, decrease of 0.6%, and only during the last period of simulation.

Such results are attributed to the water availability feedback that altered the model behavior in response to the decreased water supply during the period 2036-2040. Figure 4.14(a) shows the change in the water storage available for the irrigation districts. A water deficit is assumed to exist when the storage in irrigation district-owned reservoirs (approximately ~1.1 bcm) is completely depleted. The figure shows the weekly changes in the storage that result from river diversions and irrigation withdrawals. For the base case scenario, the storage decreased from 2035 onwards due to a significant decrease in the simulated water supply. That decrease triggered the model feedback and resulted in the allocation of the available water based on the economic return of each crop, and thus allocated less than the optimum water requirement for alfalfa, and the total yield decreased. The decrease in the yield then resulted in a decrease in the LEI for 2036-2040 compared to the base case.

The “business as planned” adaptation policy set assumed a 5% increase in storage, starting in 2025 with a lag period of 5 years to be completed in 2030, for expansion of existing storage or construction of new reservoirs. While the water deficit occurred for the “business as planned” (BAP_CM$_{CC}$_85_ PS$_{BAP}$) scenario, its effect was partly offset by the increase in the storage and thus the decrease in crop yields was limited. In contrast, for the second scenario in the group (BAP_CM$_{CC}$_85_ PS$_{HA}$), the implementation of the high adaptation policy alternatives resulted in no shortage at any time during the simulation, and more interestingly, generated a decrease in the total water withdrawals compared to the BC scenario while maintaining a steady expansion rate – see Figure 4.14(b).

We compared the two BAP scenarios under an unlimited water supply to investigate the importance of the feedback structure of the irrigation system. Results are summarized in Table 4.7. For the most part, the results for the various indicators were identical except for the last period after 2035 where the supply decreased significantly. The BAP_CM$_{CC}$_85_ PS$_{BAP}$ scenario under an unlimited water supply showed an increase of 15.5% for withdrawals compared to 4.6% under the ensemble mean water supply with respect to the BC scenario. In BAP_CM$_{CC}$_85_ PS$_{HA}$, no changes were observed.

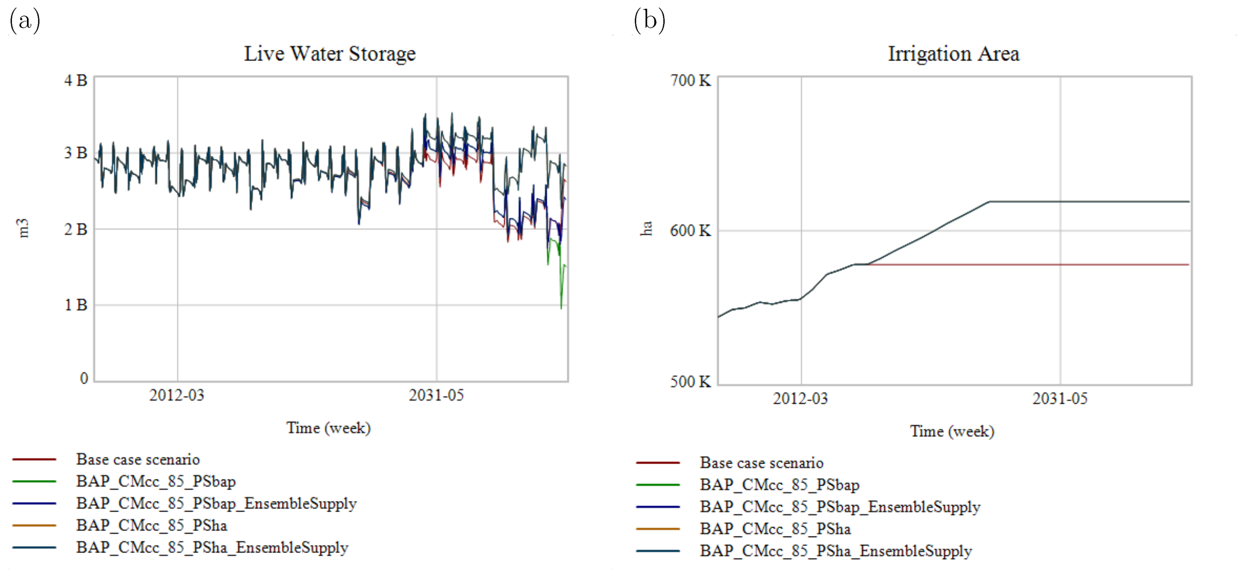

Figure 4.14. Simulated water storage (a) and irrigation area (b) for the "business as planned" scenarios in S6

Table 4.7. Percentage change for "business as planned" scenario group under different policy alternatives with unlimited and actual water supply simulated using the hydrologic model

Variable	Period	Scenario				
			Unlimited water supply		Ensemble model water supply	
		BC	BAP_CM$_{CC}$ _85_PS$_{BAP}$	BAP_CM$_{CC}$ _85_PS$_{HA}$	BAP_CM$_{CC}$ _85_PS$_{BAP}$	BAP_CM$_{CC}$ _85_PS$_{HA}$
Land productivity index						
	2016-2020	0	0	0	0	0
	2021-2025	0	0	0	0	0
	2026-2030	0	0	0	0	0
	2031-2035	0	0	0	0	0
	2036-2040*	0	**6.87**	6.87	**-0.62**	6.87
Water economic index						
	2016-2020	0	1.18	2.00	1.18	2.00
	2021-2025	0	3.94	6.67	3.94	6.67
	2026-2030	0	5.24	12.90	5.24	12.90
	2031-2035	0	5.24	20.34	5.24	20.34
	2036-2040	0	**-2.41**	17.95	**1.29**	17.95
Land economic index						
	2016-2020	0	0	0.07	0	0.07
	2021-2025	0	0	0.21	0	0.21
	2026-2030	0	0	0.28	0	0.28
	2031-2035	0	0	0.37	0	0.37
	2036-2040	0	**7.75**	8.45	**-1.09**	8.45
Irrigation water withdrawal						
	2016-2020	0	0.25	-0.31	0.25	-0.31
	2021-2025	0	1.25	-1.13	1.25	-1.13
	2026-2030	0	1.71	-4.13	1.71	-4.13
	2031-2035	0	1.71	-9.80	1.71	-9.80
	2036-2040	0	**15.48**	-3.50	**4.57**	-3.50

* bold text refers to estimation points affected by the feedback of the model

The results of the two other scenarios, RD_CM$_{WI}$_85_PS$_{DC}$ and RD_CM$_{HV}$_85_PS$_{HA}$, are shown in the supplementary material section 6. The rapid development RD_CM$_{WI}$_85_PS$_{DC}$ scenario showed a gradual increase in the total withdrawals to 15.9% by 2035 and slight increases for all the three indictors with 2.2% for the WEI, 5.9% for the LEI, and 8.7% for the LPI. However, the irrigation sector did not maintain the expansion rate beyond 2035 due to the shortage generated. In contrast, with the high adaptation policy set in RD_CM$_{HV}$_85_PS$_{HA}$ scenario, the irrigation withdrawals decreased for all the periods except for 2036-2040, which generated a slight increase of 5.2% compared to the base case scenario. Both the WEI and LEI increased significantly by 50.8% and 37.7% by 2040, respectively. This is an interesting result, as the irrigated land area reached approximately 700,000 hectares (expansion of almost 22% from the BC scenario), yet the model did not simulate a water shortage. In RD_CM$_{HV}$_85_PS$_{HA}$, water storage increased by 10% prior to the decreased ensemble water supply by the hydrologic model in 2035. These findings have significant implications on the choice of policy alternatives to address future water demands due to both expansion of the irrigation areas and climate change.

4.7 Conclusions

To better inform water resources decision making at a basin scale, there is a need for accurate and transparent policy assessment tools that can quantify impacts inexpensively and allow stakeholder participation. Here, we developed the Alberta Irrigation Scenario Simulator (AISS), which is intended to broaden the perspectives of researchers, water resources managers, policy analysts and decision makers, and irrigation managers through learning the possibilities and limitations of irrigation expansion using a feedback-driven system. AISS is particularly useful for strategic planning through scenario analysis. Specifically, it allows a transparent policymaking process, as well as translation of a wide range of policy questions into scenarios that can be easily interpreted by decision makers. We developed a set of scenario groups and combinations that cover a wide range of plausible future changes, and whose results may stimulate policymakers to consider other expansion scenarios and/or interventions than investigated to date.

We showed the importance of the feedback structure on the estimation of future irrigation water withdrawals and its impact on the economic returns to the irrigators. Trade-offs were analyzed in the presence of limited water supply derived using a physically-distributed hydrologic model with an ensemble of five climate models. In particular, we found that the irrigation sector in southern Alberta faces a generally positive outlook for expansion, under the right adaptation strategies in the presence of climate change. Crop yield trends for the six major irrigated crops showed continuous increases to 2040, with relatively small increases in irrigation demands due to climate change of 7% and 11% period for the two GHG emissions scenarios, RCP 2.6 and RCP 8.5 in 2036-2040, respectively. Our findings showed that the irrigation sector of Alberta could maintain the planned expansion goal to 625,000 hectares by 2025 set by policymakers in the province with the adoption of appropriate measures of efficiency increases and expansion of the existing total storage by 10%. Otherwise, water shortages will negatively affect the irrigation sector. The irrigation sector could potentially expand beyond the goal of 2025 to reach 703,000 hectares by 2040 with shifting to high-value crop mix and increasing the irrigation application efficiency up to 90% by 2040. In that case, the irrigation demands are only expected to increase by 5.2% in 2036-2040.

The aim of AISS was to depart from deepening knowledge vertically in describing the soil-plant-atmosphere interactions to expanding the knowledge into a wider perspective by incorporating the socioeconomic and infrastructural components of an irrigated agriculture system. However, the model assumes a uniform diffusion of new irrigation application technologies across the irrigated land area. This assumption was necessary to upscale the application of the model from the field scale to the basin scale, but this simplified treatment of spatial heterogeneity is a general limitation of system dynamics modeling. This is one of the trade-offs of aggregation into larger units for simulation (Holzworth et al., 2015) which could potentially be addressed in future work by using spatiotemporal system dynamics that connects the temporal model to a GIS database. Moreover, AISS model could benefit from disaggregating different reservoirs for accurate evaporation area estimation and for incorporating individual reservoir operation rules. Therefore, a spatiotemporal model may improve results at the cost of significant modeling effort.

Finally, this work fills a gap in our basin-scale understanding of the impacts of expansion scenarios, crop mix ratios, and various policy interventions, compounded with climate change and future supply on future irrigation demands and irrigation withdrawals. Such basin-scale models help characterize impacts at scales at which policy decisions are made. The modeling work presented here contributes to the growing efforts of agricultural modeling communities to develop models for application at broader scales with respect to time and space for policy assessment.

Chapter 5. Summary, conclusions, and recommendations

5.1 Summary

Challenges in modeling irrigated agricultural systems arise when incorporating various aspects like farm economics, changes in infrastructure and irrigation systems, reservoir storage and operation, social license to operate and divert water, as well as, hydrological changes that alter water supplies, temperatures, and precipitation patterns that result from climate change. Consequently, and because of the complex nature of such large systems, feedback relationships arise between the different factors. These interactions necessitate modeling the bigger picture while maintaining accurate crop production. Crop models typically operate at a field scale and short time frames (i.e., a growing season), which is suitable for improving our understanding of the impacts of water moisture conditions and agronomic traits on crop yields. The usage of such models limits assessments to on-farm management options. Therefore, integrated models are crucial for evaluating, and potentially understanding, complex interactions and trade-offs among policy choices and socioeconomic, technical, and environmental processes (Kelly et al., 2013); further, such models typically require long simulation periods – from multi-year to multi-decadal – to permit long-term impacts to emerge and accumulate. However, integrating across scales implies shifting into a coarser simulation time step that could allow enough time for the system to accumulate effects and recognize impacts – such as those needed for long-term policy assessment.

It is important that a crop model link to models of other disciplines and include a broad representation of the processes involved. Thus, if a process-based crop growth model is built in a systems model that identifies and quantifies the linkages between irrigated agriculture and the socioeconomic and policy factors, the responses of irrigation systems, such as that of Alberta, to policy interventions can be assessed under climate change.

The research described a newly developed process-based integrated systems model for simulating irrigation expansions at the river basin scale called Alberta Irrigation Scenario Simulator (AISS). The result is an improved characterization of the feedback mechanism between policy choices and socioeconomic, technical, and environmental processes in the context of irrigated agriculture. Simulations using AISS identify both the resiliency of Alberta's irrigation sector to future expansions and its leverage points. The model assesses the sustainability of Alberta's irrigation sector with intentions of expansion and under a range of policy instruments over the next 25 years.

5.2 Conclusions

The key conclusions from this study can be summarized in terms of the five research objectives presented in Chapter 1 as follows:

Identify potential water policy interventions for basin-level competition for water resources

- Water policies were widely divergent across scholarly publications and grey literature.
- Indeed, there is not even a clear or universal definition for the term "policy" in the literature, and in particular for the water resources community, except for a few studies that defined "policy" as a change in model parameters. A "menu" for modelers was created for water policies to address potential water shortages. This menu has 51 policy interventions for the agricultural sector, 55 for the municipal, and 31 for the industrial with relevant citations of successful modeling studies.

- Each policy intervention can yield different results and implications based on local conditions, and social, economic, and environmental characteristics of the basin under water shortage.

Find a balance between modeling scales for integration that allows long-term policy assessment while maintaining accurate crop modeling

- Aggregation of weather input data to a process-based crop growth model resulted in an overestimation of both the crop biomass and yield and the actual evapotranspiration.
- Longer simulation time steps increased the impacts of weather input data aggregation, and overestimation became more pronounced with increases in the simulation time step.
- Longer than daily simulation time steps, and specifically semi-weekly simulations, in conjunction with weekly weather input for process-based crop modeling provided sufficiently accurate results to represent the key functional responses of a crop model, e.g., the end of season yield, and seasonal water requirements.
- Using annual simulations hide the variability within the year and could underestimate the effects of water stresses on crop production in cases of water shortage. In contrast, modeling at an hourly scale produces superior crop growth simulations but is not appropriate for deciding on diversions from storage reservoirs, for example. Therefore, the irrigated agricultural system is modeled with AISS on a weekly basis, a temporal resolution that provided a useful compromise between crop growth modeling at fine-scale and policy assessment that typically require long simulation periods for the impacts to become pronounced.

- This has important implications for using process-based crop models for integrated assessments that integrate to other socioeconomic, environmental, or hydrologic models, and therefore provides guidance for modelers involved in multidisciplinary studies under including policy assessment, water and food securities, and resource use and efficiency.

Capture the complexity of irrigated agriculture in a systems model for policy assessment

- Mapping the connections between irrigation expansion and its social, economic, environmental, and policy factors using the causal loop diagram showed explicitly the feedback loops and the critical time delays that would have been otherwise ignored.
- AISS used the coarser-time-step crop growth model, called CropSD, developed in Chapter 2 as its core component for simulating crop production and estimating field water demands. CropSD runs under daily, semi-weekly, or weekly time step with weekly aggregated weather data.
- AISS integrated CropSD with four other systems components including water demand, supply and reservoir management; agricultural production economics; irrigation infrastructure; and the socioeconomic responses and perceptions of irrigators to irrigation expansion and technology adoption.

Reveal the broader consequences of expanding Alberta's irrigation sector and assess the possible impacts of climate change and policy interventions on Alberta's irrigation expansion

- The model quantified the effects of various water conversation policy alternatives and showed the anticipated trends for irrigation water demand, water diversions, crop yield changes, total production, production economics, and changes in cropping patterns to 2040.

- Crop yields for major irrigated crops in Alberta showed a gradual increase on average to 2040 (i.e., end of the simulation period) by a range of 0.031 to 0.071 t ha^{-1} per year for the RCP 8.5 scenario, while an increase by 0.023 to 0.043 t ha^{-1} per year for RCP 2.6. Further, for RCP 8.5, irrigation demands increased by 20.5% for an expansion rate of 5200 ha $year^{-1}$ until 2040 and under the existing infrastructure and physical properties of the irrigation sector. However, with appropriate policy interventions, the demands increased by only 5.2% compared to a base case scenario that assumed no expansion and maintained current adaptation measures.
- Changes in crop patterns to a water conservative crop mix that replaced 50% of alfalfa with barley and canola by 2040 resulted in a marginal decrease of the total irrigation water withdrawals of 1.5% by 2040. However, it provided higher economic returns both in terms of dollars per unit of irrigated land and dollars per unit of irrigation water withdrawal.
- Simulations by SWAT hydrologic model using an ensemble of five climate models predicted decreased water supply in the period of 2035-2040 under the RCP 8.5 scenario.
- Water deficits were generated for the planned expansion scenario and policy interventions set by the Government of Alberta (2017). The effects were partially offset by increasing the storage by 5%. Partial deficits resulted in slight decreases in crop production and thus decreases in both land productivity and economic returns.

This work fills a gap in basin-scale understanding of the impacts of irrigation expansion, changes in crop mix ratios, and adoption of various policy interventions, compounded with climate change and future supply on future irrigation demands and irrigation withdrawals. AISS characterize impacts at scales in which policy decisions are made. The modeling work presented here contributes to the growing effort of the agricultural modeling community (Capalbo et al., 2017; Ewert et al., 2015; Holzworth et al., 2015; Jones et al., 2017a) to develop models to be applied at a broader scale with respect to time and space that integrate various domains to allow for policy assessment. AISS showed the importance of incorporating feedback loops in studying irrigation expansion in Alberta. Feedbacks altered the model behavior significantly and specifically after 2035 where water supply decreased as simulated by the hydrologic model of Alberta, such that for the planned expansion scenario by the Government of Alberta, the withdrawals increased by 4.6% from the base case scenario in the period of 2035-2040. Whereas, a similar analysis that ignores the feedback effect would estimate an increase in the irrigation water withdrawals by 15.5%. Ignoring feedback effects led to a false "sense of security" to farmers and water managers that resulted in increases in irrigation withdrawals, in economic returns per unit area, and in unit crop production per unit area.

5.3 Recommendations for Future Work

The modeling work presented here and the development of AISS could benefit greatly from further improvements and extensions to its capabilities. The following are suggestions for future work to extend the use of the model and to widen its application domain:

1. AISS could benefit from integrating a livestock production system to represent the interaction between cropping and livestock systems. The livestock component should communicate with the systems model by driving the demands for forage crops, altering water demands and withdrawals based on simulated livestock heads. Integrating the livestock component would also necessitate the development of an environmental component that traces the manure production and the impacts of manure applications on soil nutrients, which may affect crop production.
2. Building up on recommendation number 2: develop and integrate a process-based soil nutrients balance in system dynamics framework to refine the impacts of fertilizers on crop yields of AISS.
3. AISS deals with the spatial variability through treating the different fields as arrayed compartments that describe homogenous subareas each with different crop type but similar key characteristics (e.g., soil properties, weather variability, or irrigation infrastructure improvements). This could be improved by linking the temporal model into a GIS database to form a spatiotemporal system dynamics model. Such a step will also improve the allocation of the irrigation expanded land area appropriately. Expansion depends on the availability of the land and its suitability for agriculture as well as its location relative to the irrigation infrastructure. That improvement will also allow modeling separately the different reservoirs for accurate evaporation area estimation and for incorporating individual reservoir operation rules.

4. Due to the complexity of the interactions of the irrigated agricultural system with the socioeconomic and policy factors, and the uncertainty of the socioeconomic responses to changes in the model drivers, a detailed sensitivity analysis is needed.
5. Improve the socioeconomic response of the model in terms of the decision scores developed in AISS based on actual survey data and/or interviews with stakeholders. That could include water managers, government personnel, irrigators, agricultural economists, and academics. In addition, extensive literature reviews for such responses could also guide the assignment of the different weights of each of the factors that contribute to the total decision score, both for irrigation expansion, and for improved irrigation technologies adoption.
6. Finally, the model can be used to implement the concepts of Integrated Water Resources Management (IWRM) through coupling AISS with other river basin scale models of different water sectors including municipal, industrial, or environmental water sectors. That will also allow to model the competition between water sectors and provide answers to water allocation questions in the presence of feedbacks.

5.4 Other Recommendations

The recommendations in this section focus on general recommendations for the water resources and agricultural systems modeling communities.

- It is important for model developers to consider code documentation and reusability of their developed models a priority so that expansion outside the domain of the code/model developers is achievable. It is one of the long-standing challenges identified by Holzworth et al. (2015) where most current models rely on their legacy codes that were written using procedural languages. While they are still performing well, they are not smoothly progressive towards modern code base.

- The involvement of modelers in the policy making and implementation process should not be an afterthought. Likewise, the involvement of stakeholders in model building, validation, and scenario planning should be a priority to systems modelers.

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Appendix A: Alberta Irrigaton Scenario Simulator: Model Description, Use Guide, and Model Code

This appendix describes the different components of the Alberta Irrigation Scenario Simulator (AISS), its modeling interface, inputs and input files, and how to run the model and set parameters for policy assessments. The appendix also provides the model code in terms of the model constants, model lookup functions, model subscripts, model levels and auxiliary variables, as well as the units of the different variables of the model. This appendix is supplemented with the information provided for the model development as discussed in both Chapter 2 and Chapter 4. Therefore, this document is not a standalone but rather complements the model description provided earlier.

A1 Model Components

This section describes the Alberta Irrigation Scenario Simulator (AISS) model, its assumptions, and provides its equations. The figures shown below clarify how the different model variables interact and how they are connected to each other. The model is implemented in a system dynamics interface called Vensim DSS, which is available for purchase from the Ventana Systems, Inc. website, at http://www.vensim.com.

The guide for installing Vensim and the user's guide can also be accessed through the website of Vensim, at http://www.vensim.com/docs/.

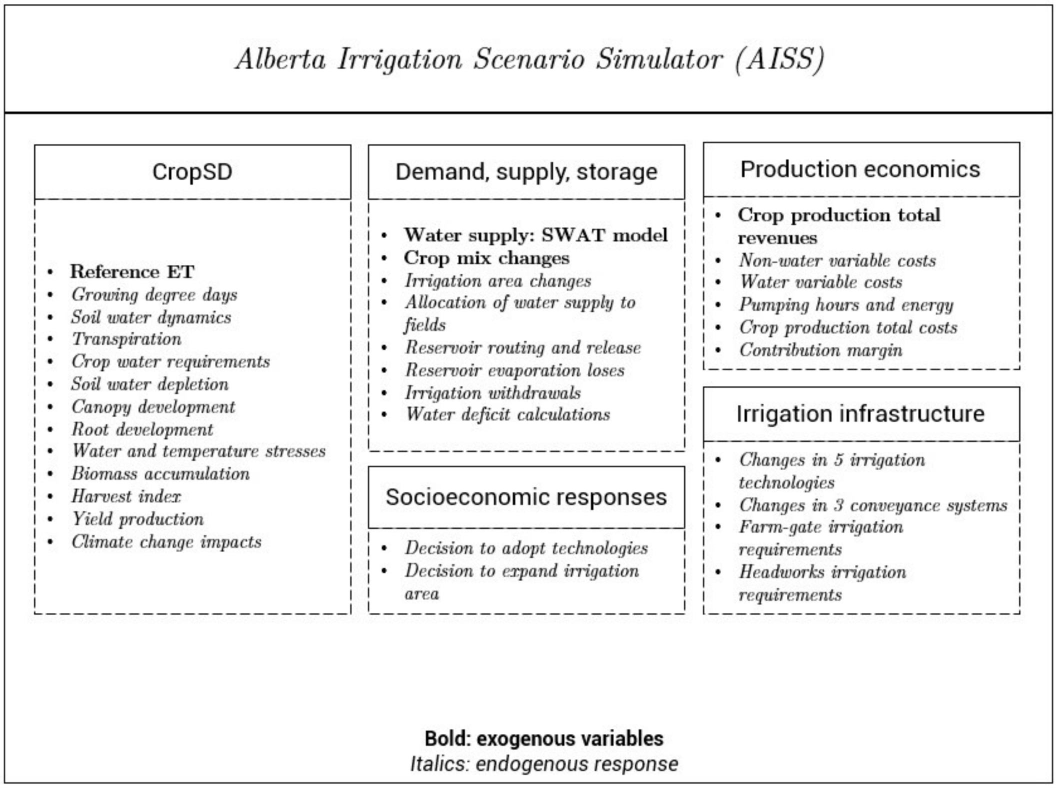


Figure A1. Simplified schematic diagram of AISS model components with the key endogenous and exogenous model variables

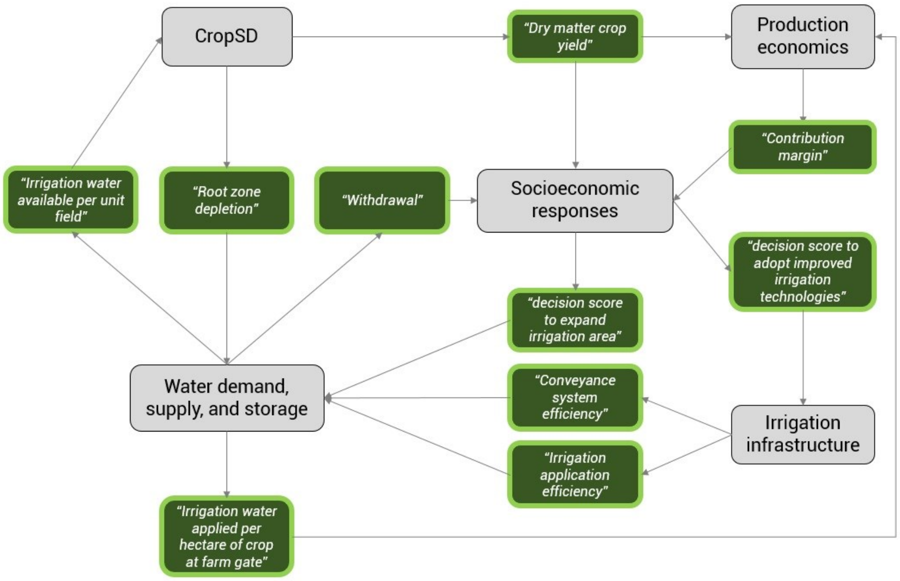


Figure A2. Key model variables that link model components. Grey shapes are the five model components and the green shapes are the key variables at which the model components exchange information

In Vensim, division of the model into five components is organized by 'views' as shown in Figure A3. Therefore, in AISS, each of the model components described in Chapter 4 and shown in Figure A1, as well as their constituent sub-components, represents a 'view'. There are fourteen views in total. These fourteen views can be accessed in Vensim through the 'view selector' at the bottom left of the main screen, as shown in Figure A3, or by pressing the 'page up' or 'page down' keys. The fourteen views are shown in Figure A4 to Figure A20, and are described in Table A1.

The model outputs in the form of figures can be accessed through the last view, called "Policy Control". This view is described in detail in the Model Inputs through Excel section of this appendix.

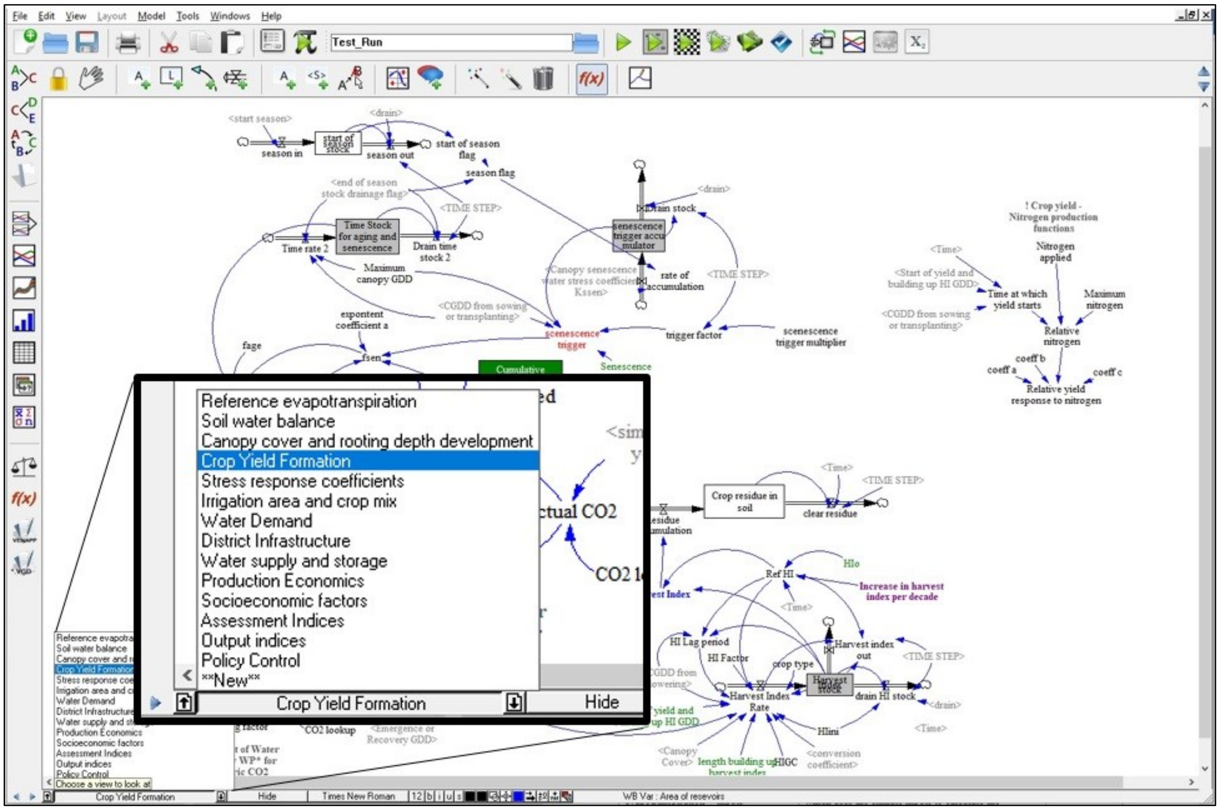
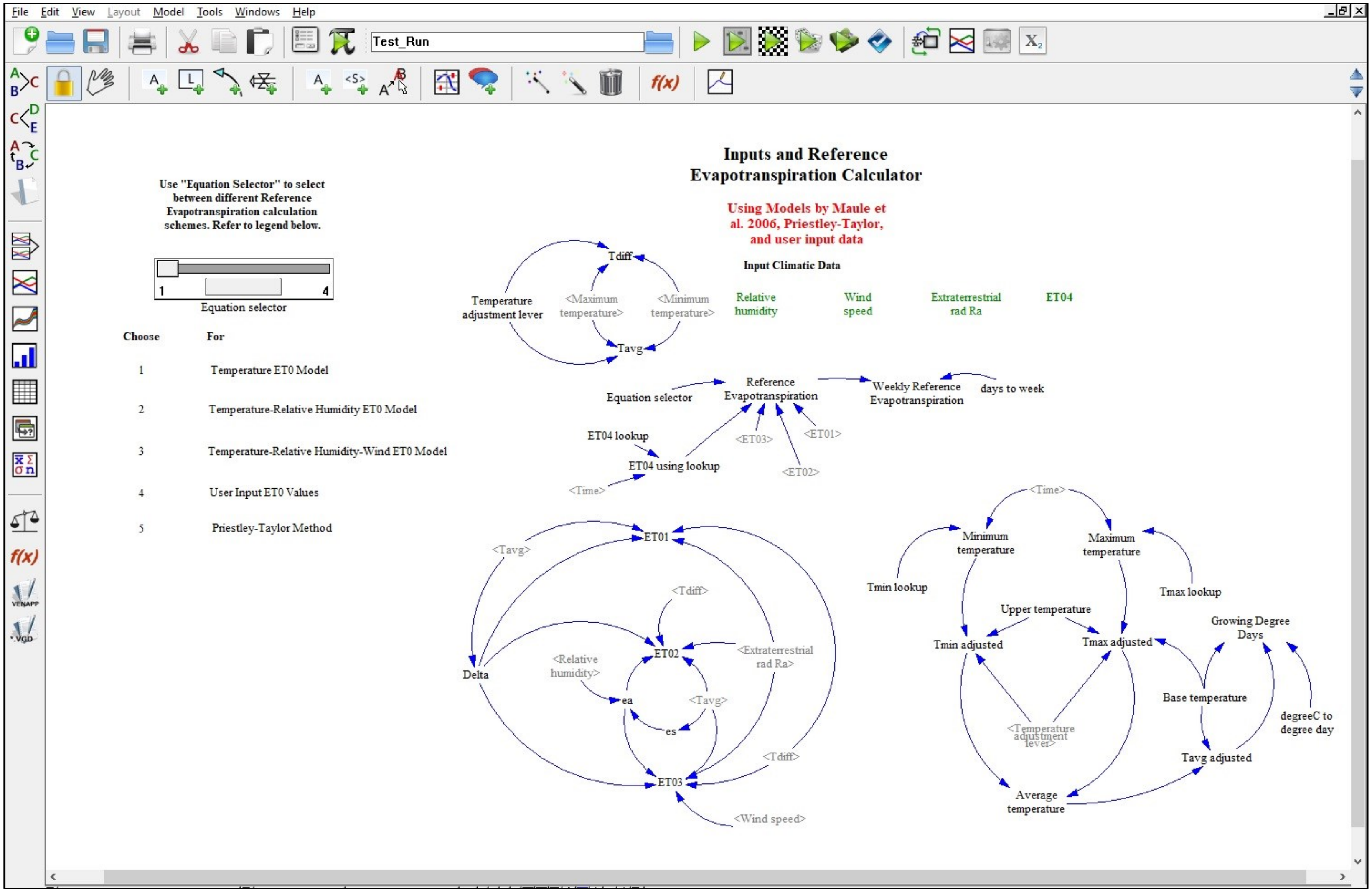


Figure A3. Different views and the location of the "*View*" selector in Vensim



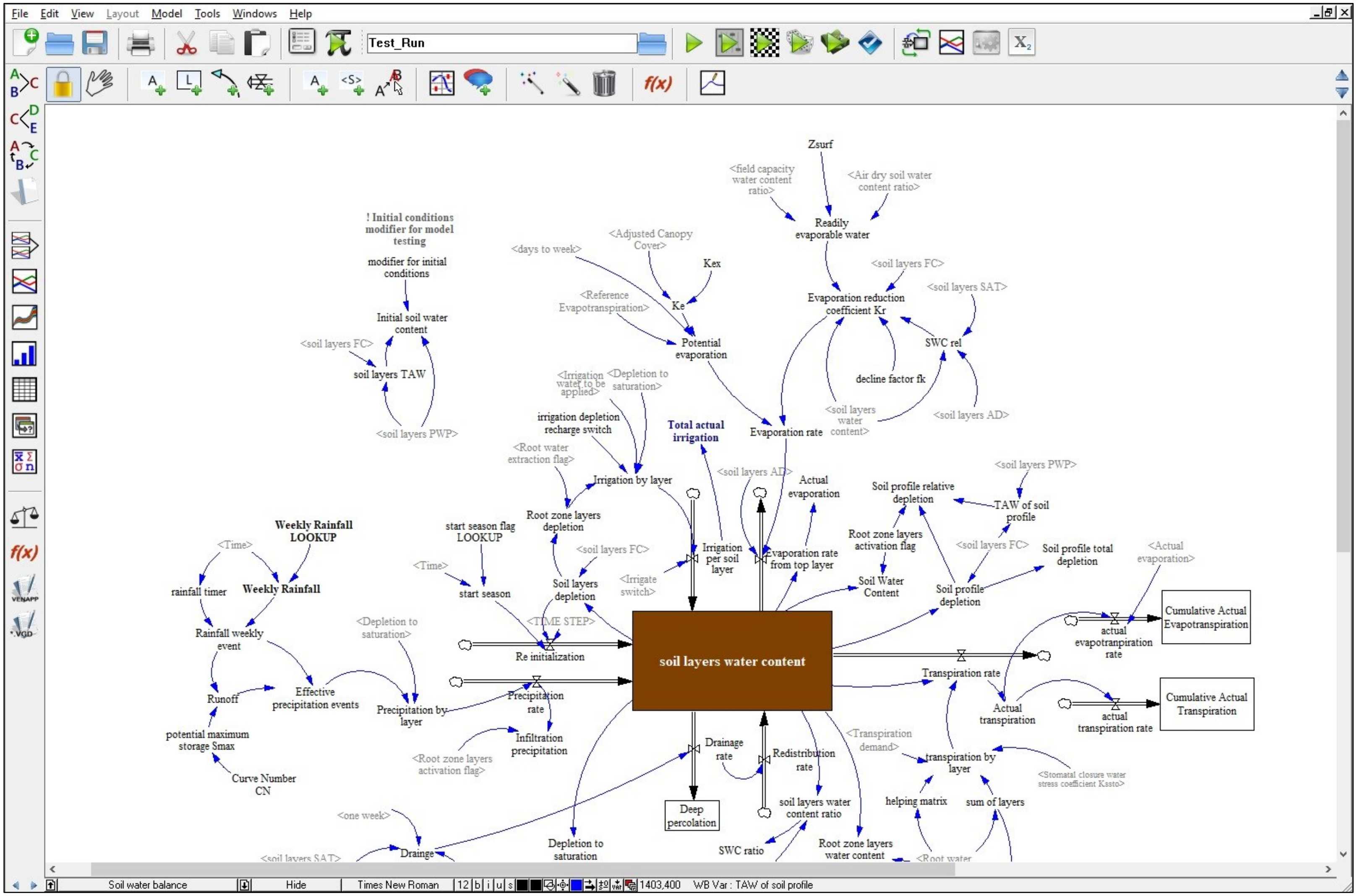
Inputs and Reference Evapotranspiration Calculator

Using Models by Maule et al. 2006, Priestley-Taylor, and user input data

Use "Equation Selector" to select between different Reference Evapotranspiration calculation schemes. Refer to legend below.

Choose	For
1	Temperature ET0 Model
2	Temperature-Relative Humidity ET0 Model
3	Temperature-Relative Humidity-Wind ET0 Model
4	User Input ET0 Values
5	Priestley-Taylor Method

Figure A4. Model climate inputs


File
Edit
View
Layout
Model
Tools
Windows
Help
Test_Run
f(x)
X2
! Initial conditions modifier for model testing
modifier for initial conditions
Initial soil water content
<soil layers FC>
soil layers TAW
<soil layers PWP>
<days to week>
<Adjusted Canopy Cover>
Kex
Ke
<Reference Evapotranspiration>
Potential evaporation
Zsurf
<field capacity water content ratio>
<Air dry soil water content ratio>
Readily evaporable water
<soil layers FC>
<soil layers SAT>
Evaporation reduction coefficient Kr
SWC rel
decline factor fk
<soil layers water content>
<soil layers AD>
Evaporation rate
<Irrigation water to be applied>
<Depletion to saturation>
irrigation depletion recharge switch
Total actual irrigation
<Root water extraction flag>
Irrigation by layer
<soil layers AD>
Actual evaporation
Soil profile relative depletion
<soil layers PWP>
TAW of soil profile
Root zone layers depletion
Weekly Rainfall LOOKUP
start season flag LOOKUP
<Time>
<Time>
rainfall timer
Weekly Rainfall
start season
<soil layers FC>
Soil layers depletion
<Irrigate switch>
Irrigation per soil layer
Evaporation rate from top layer
Root zone layers activation flag
Soil Water Content
<soil layers FC>
Soil profile depletion
Soil profile total depletion
<Actual evaporation>
<TIME STEP>
Rainfall weekly event
<Depletion to saturation>
Re initialization
soil layers water content
Cumulative Actual Evapotranspiration
actual evapotranpiration rate
Transpiration rate
Runoff
Effective precipitation events
Precipitation by layer
Precipitation rate
Actual transpiration
actual transpiration rate
Cumulative Actual Transpiration
potential maximum storage Smax
Infiltration precipitation
<Root zone layers activation flag>
Drainage rate
Redistribution rate
<Transpiration demand>
transpiration by layer
<Stomatal closure water stress coefficient Kssto>
Curve Number CN
Deep percolation
soil layers water content ratio
helping matrix
sum of layers
<one week>
Drainge
<soil layers SAT>
Depletion to saturation
SWC ratio
Root zone layers water content
<Root water
Soil water balance
Hide
Times New Roman
12
b
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1403,400
WB Var : TAW of soil profile

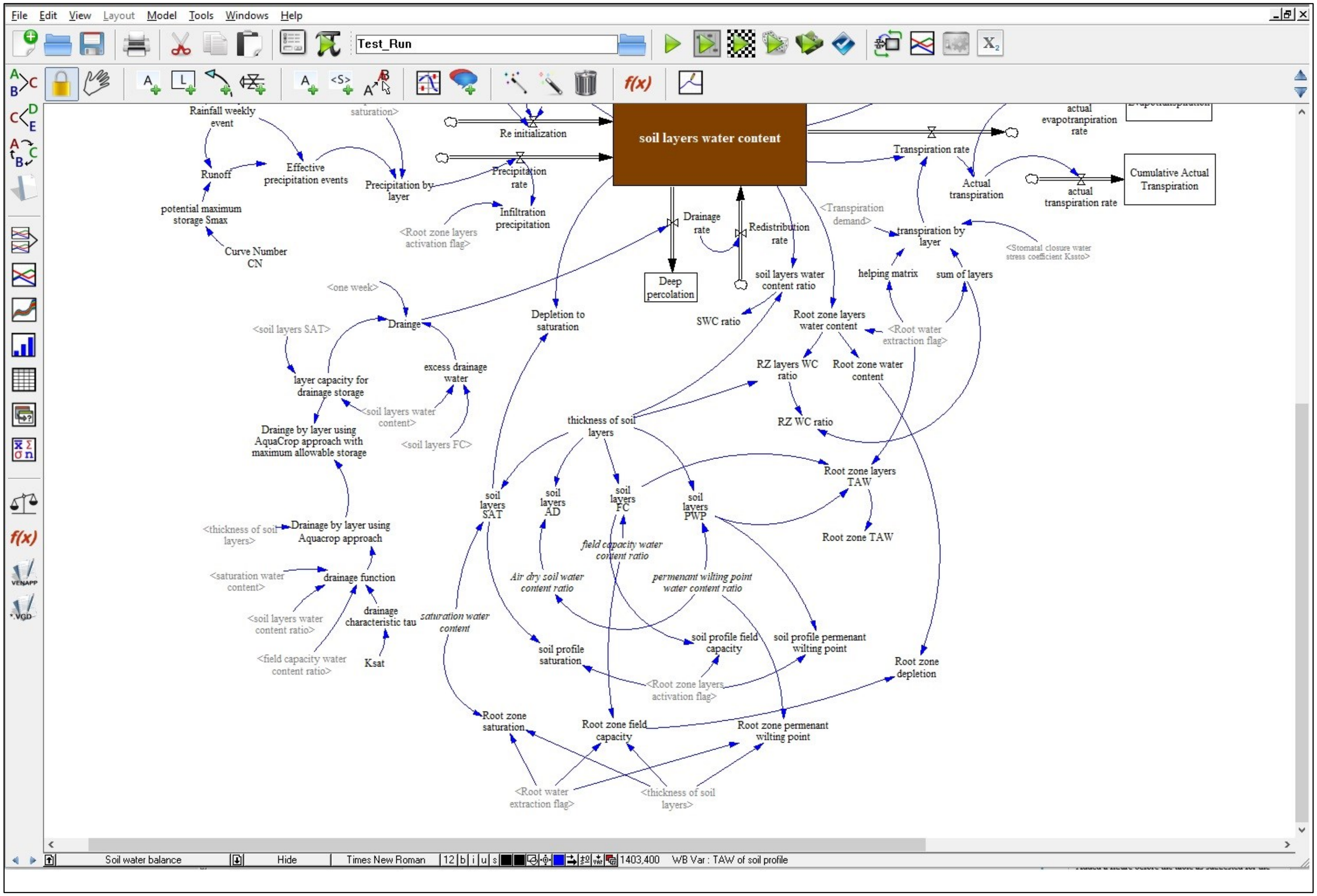


Figure A5. Soil water dynamics component

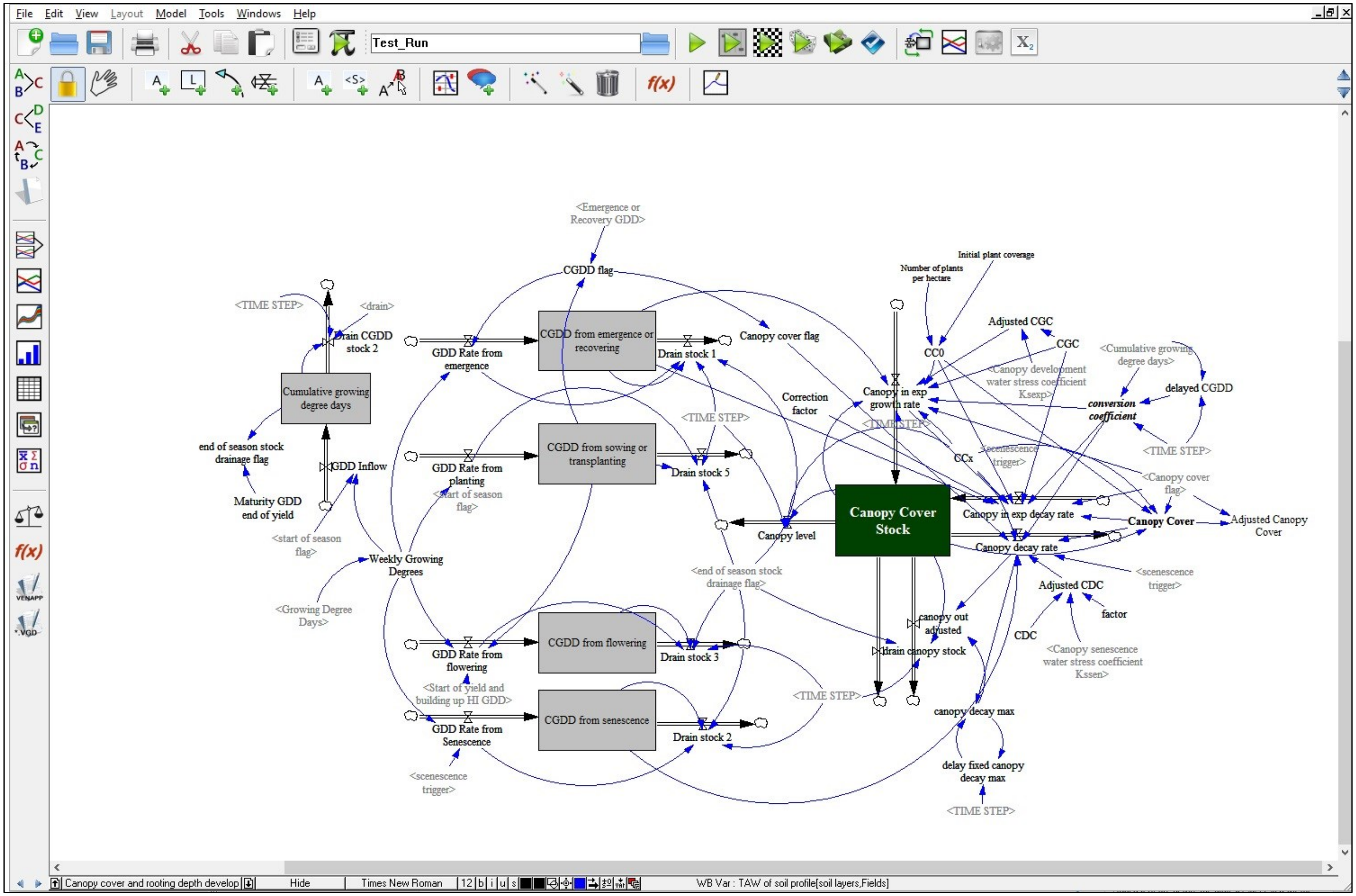


Figure A6. Canopy cover development

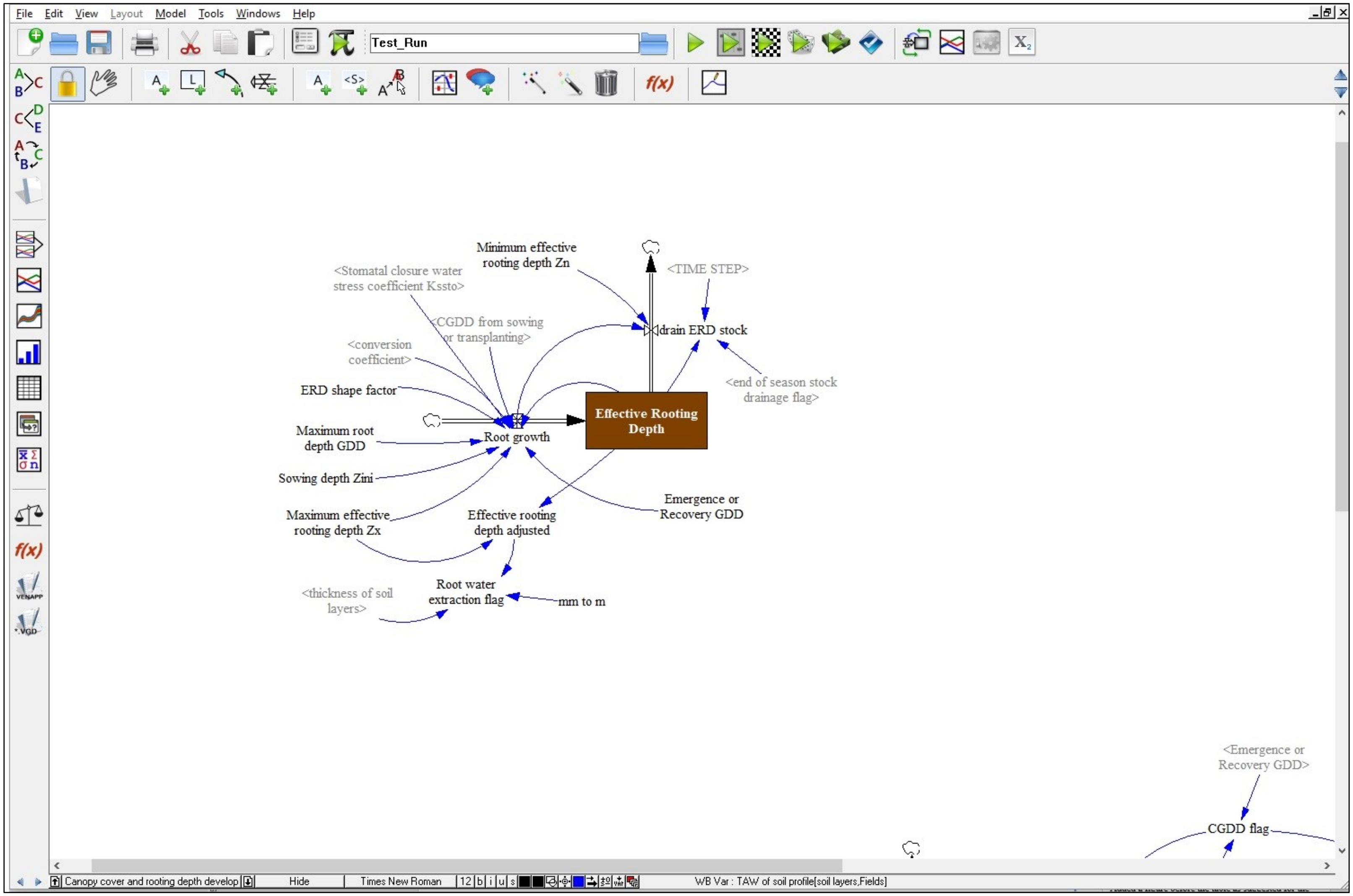


Figure A7. Effective rooting depth

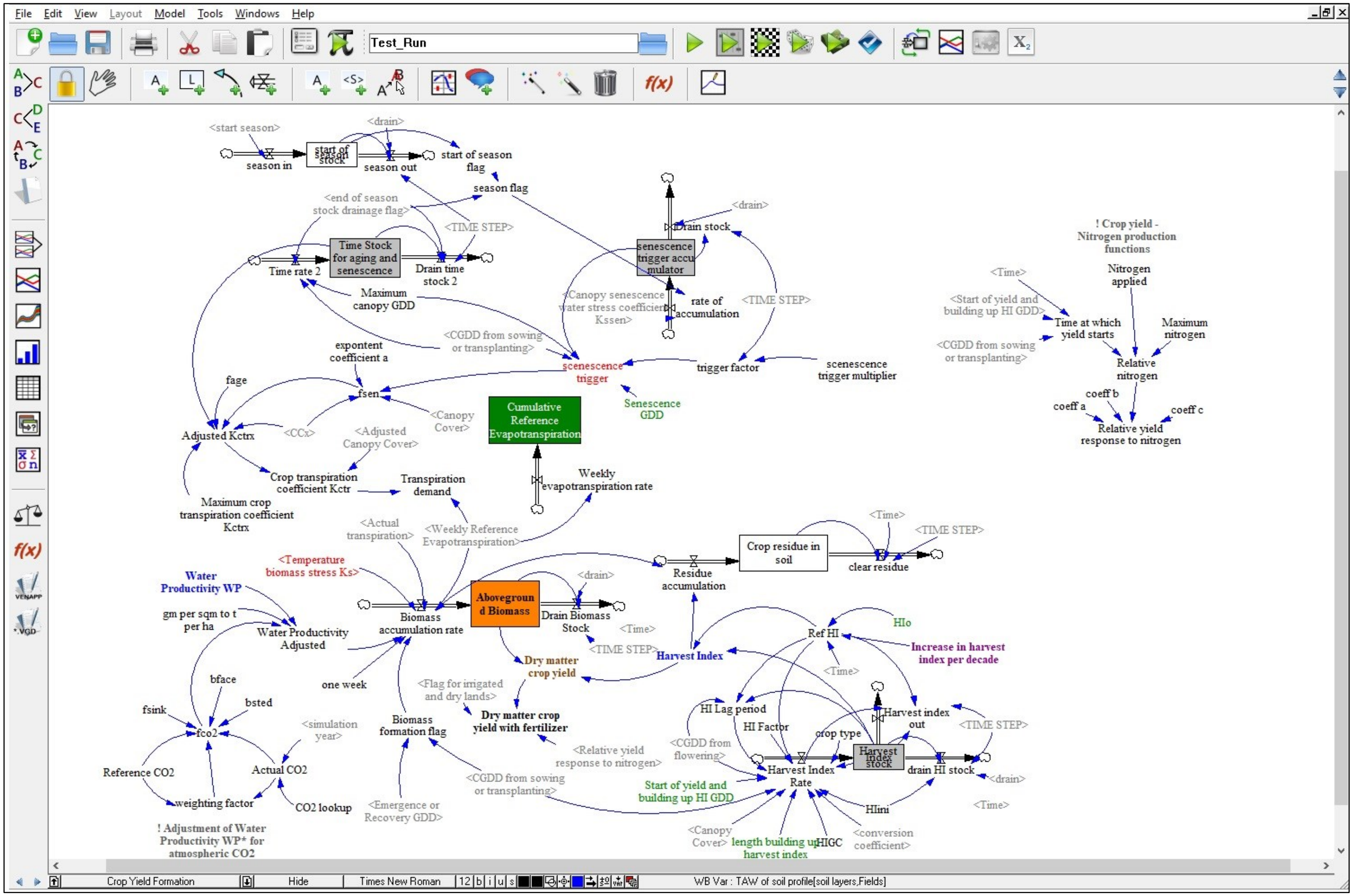


Figure A8. Biomass and crop yield calculations

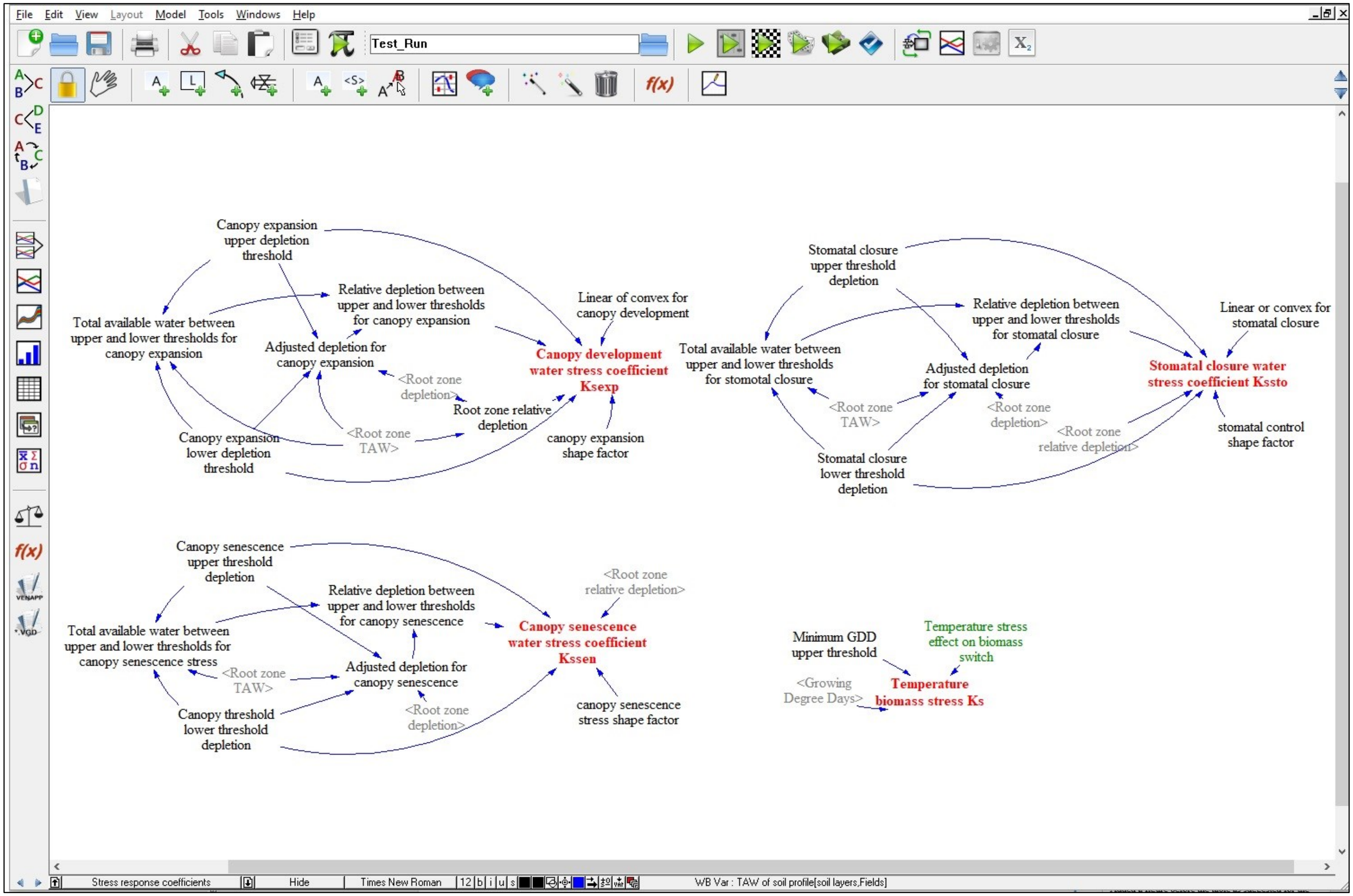


Figure A9. Water and temperature stresses

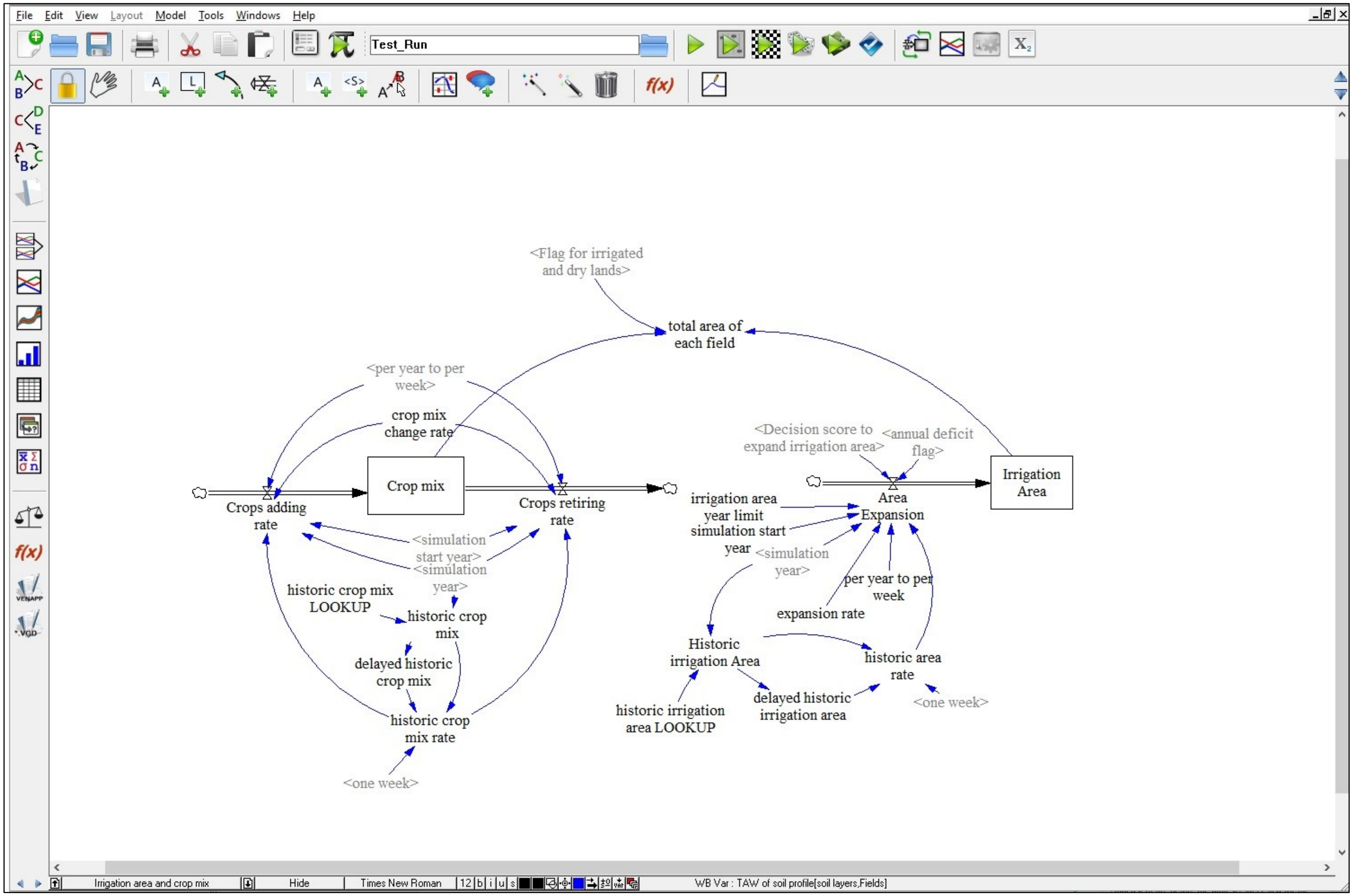


Figure A10. Changes in crop mix and irrigation area

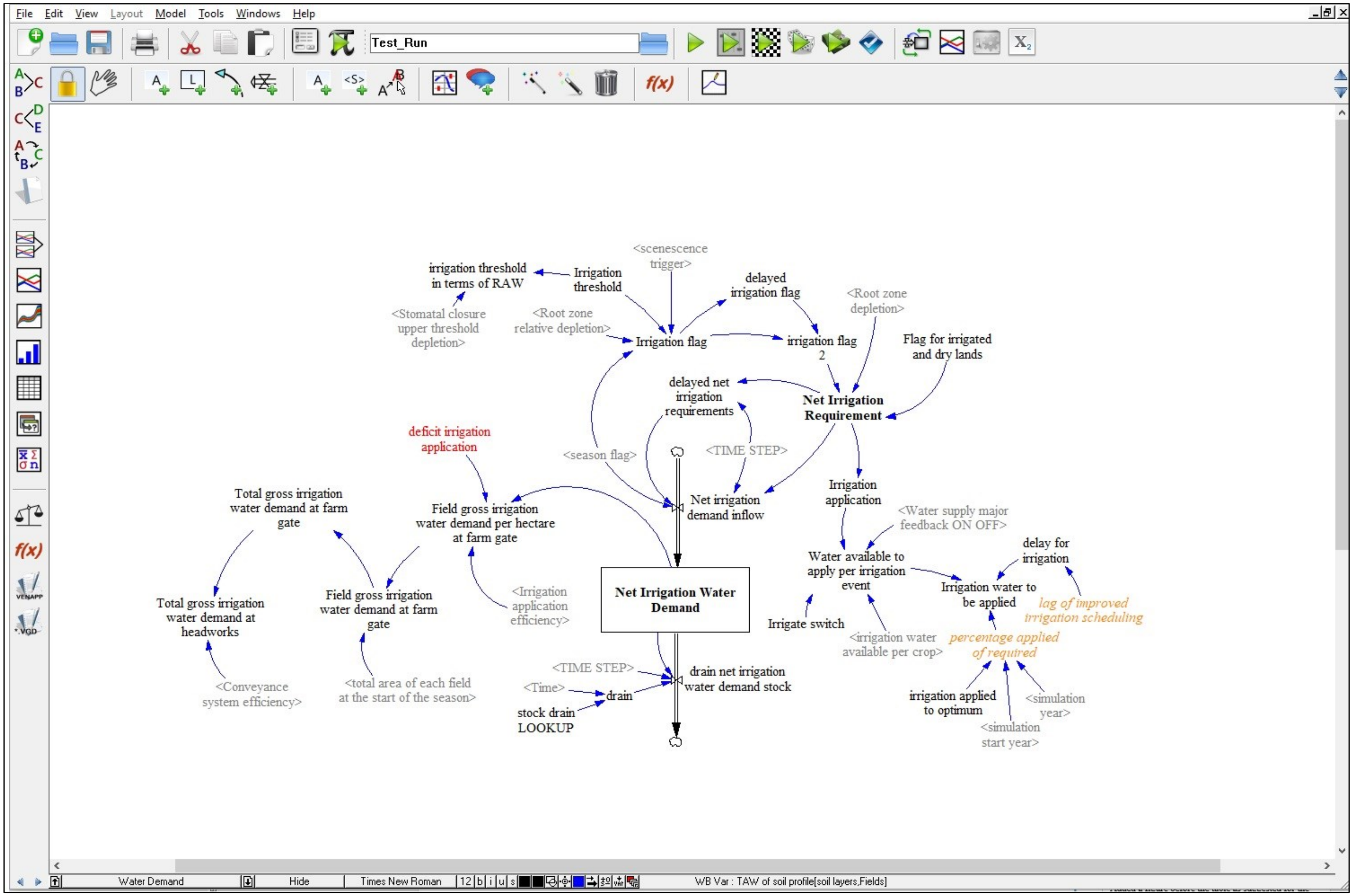


Figure A11. Irrigation water requirements and management

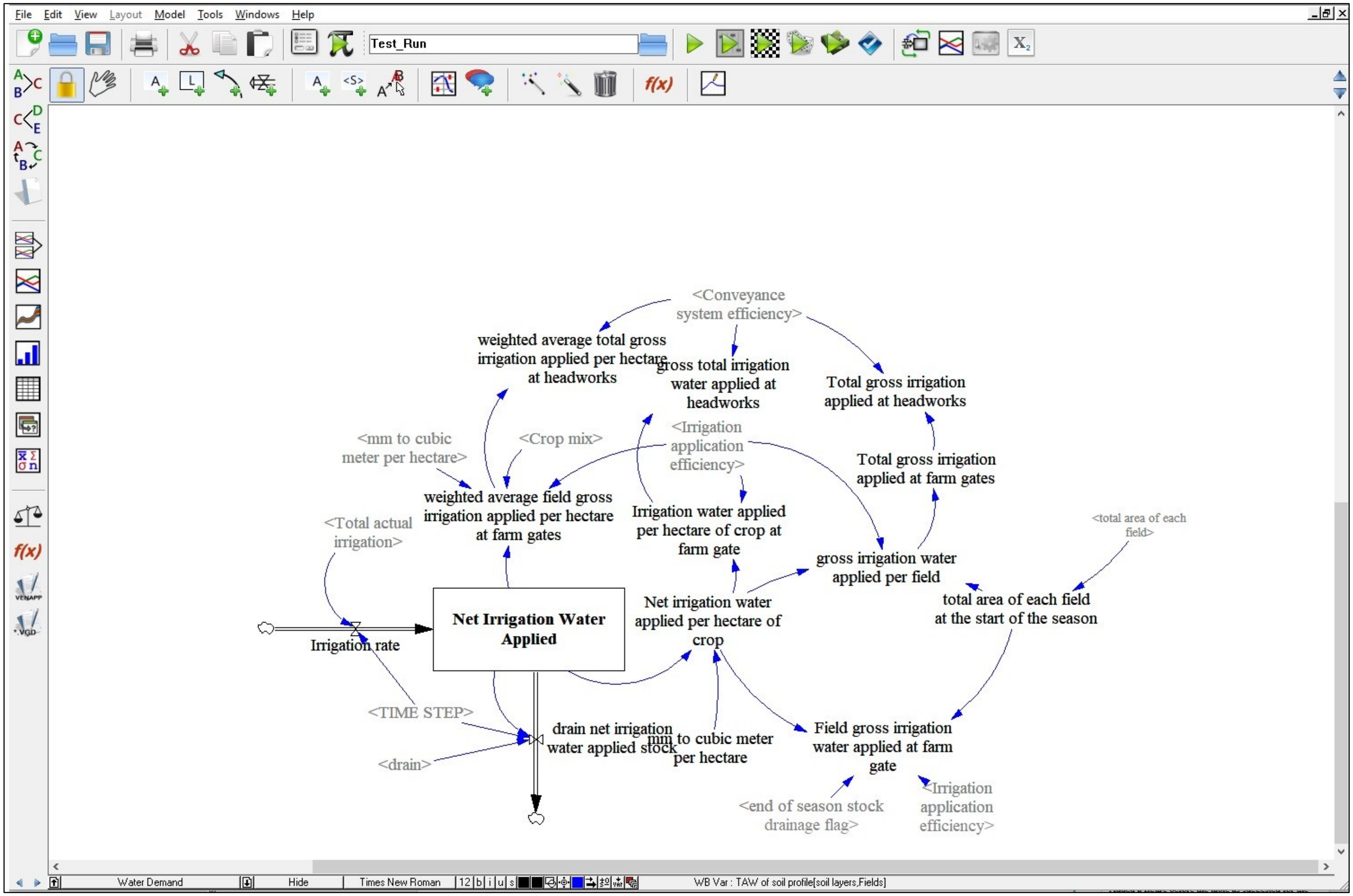


Figure A12. Irrigation water application

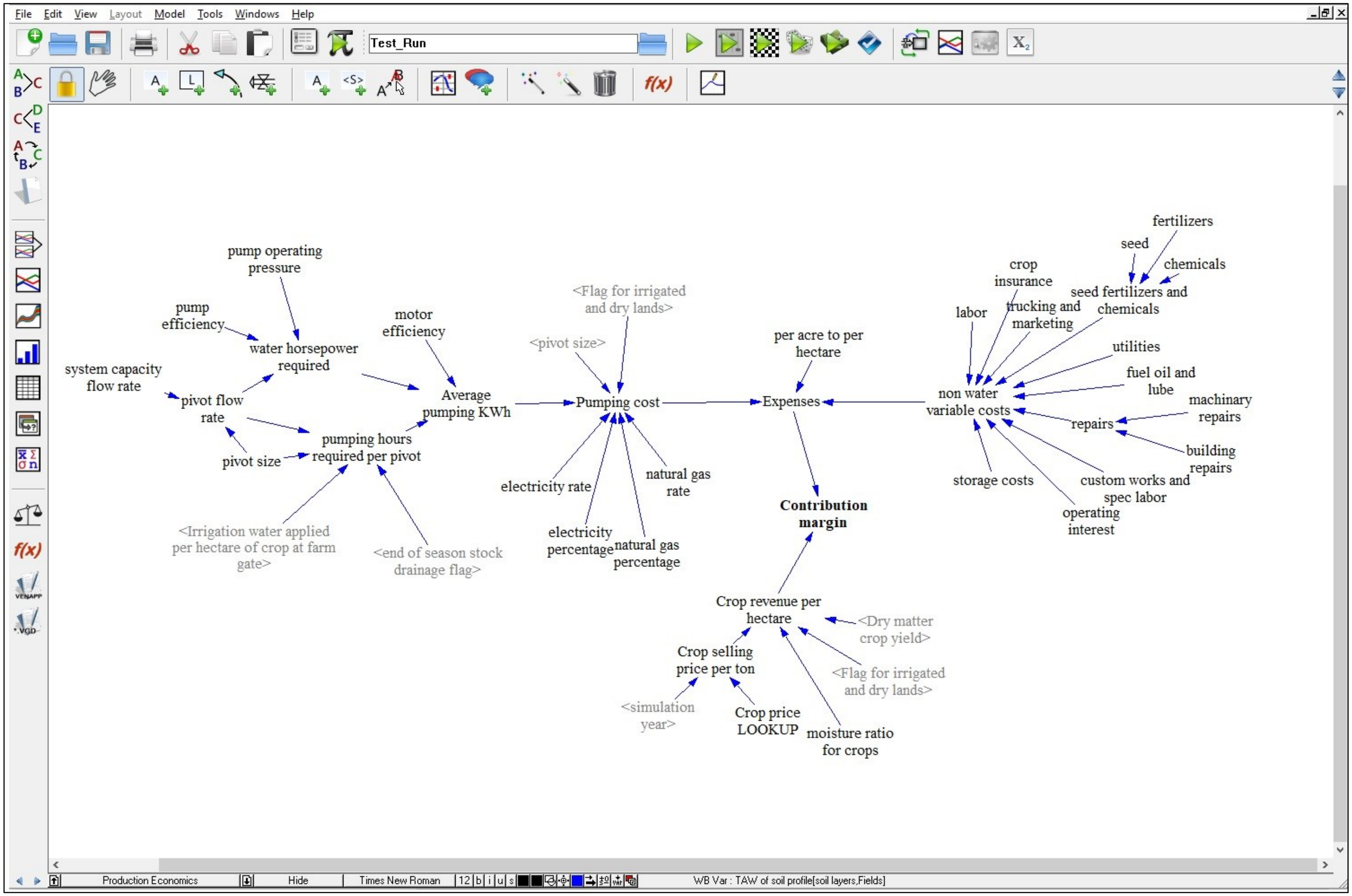


Figure A13. Agricultural production economics

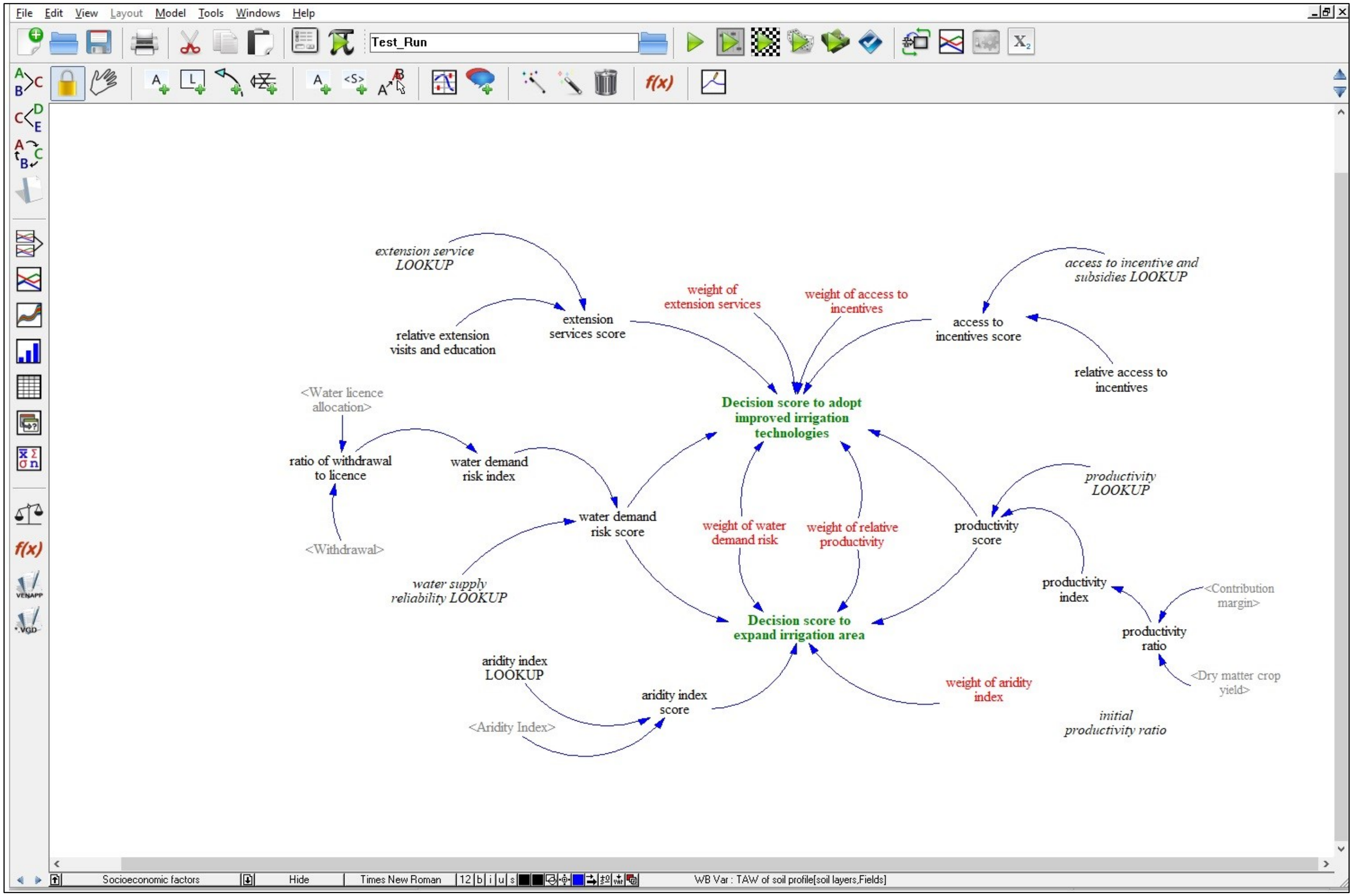


Figure A14. Socioeconomic responses of the irrigation sector

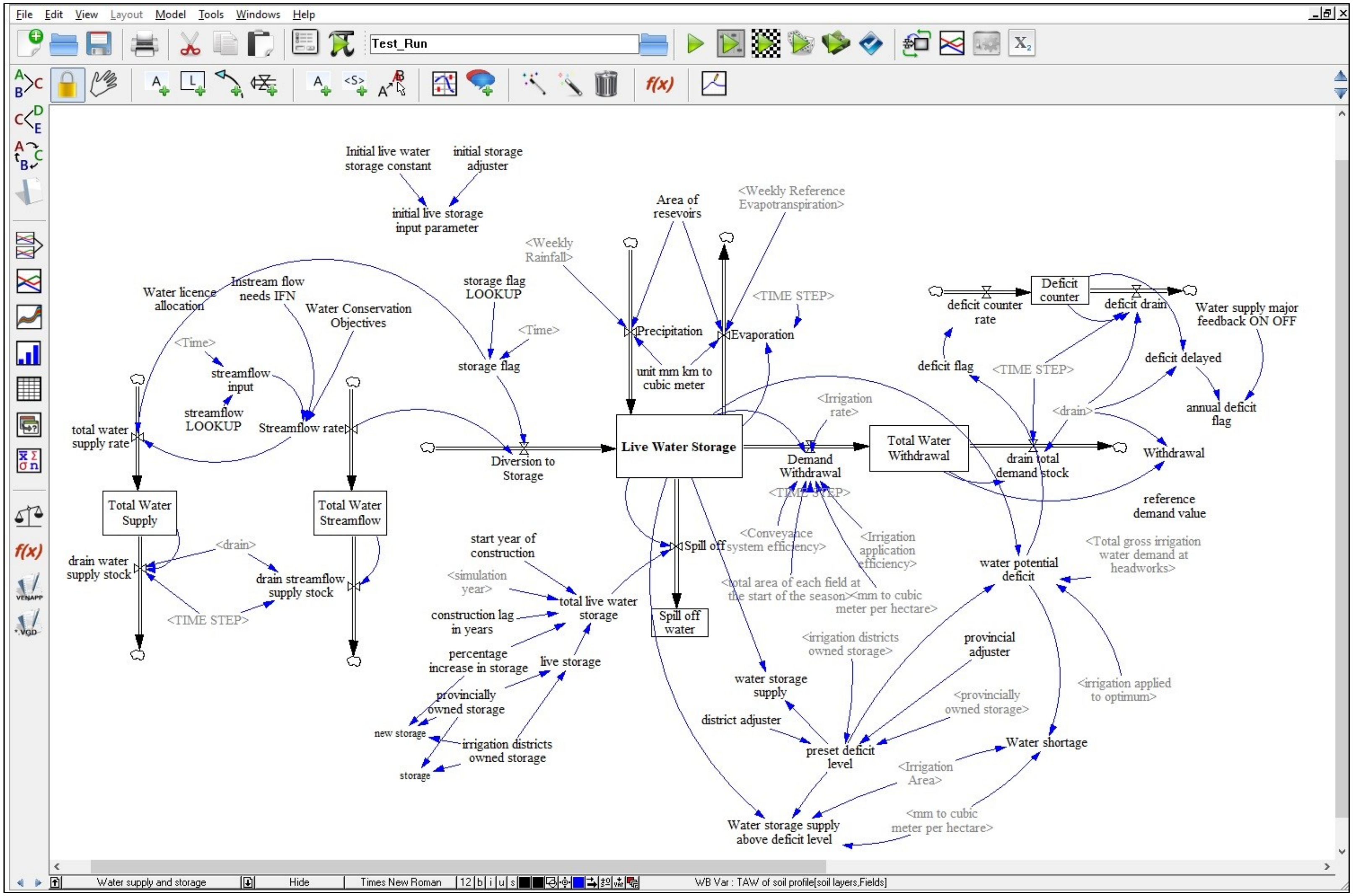


Figure A15. Water storage and water supply

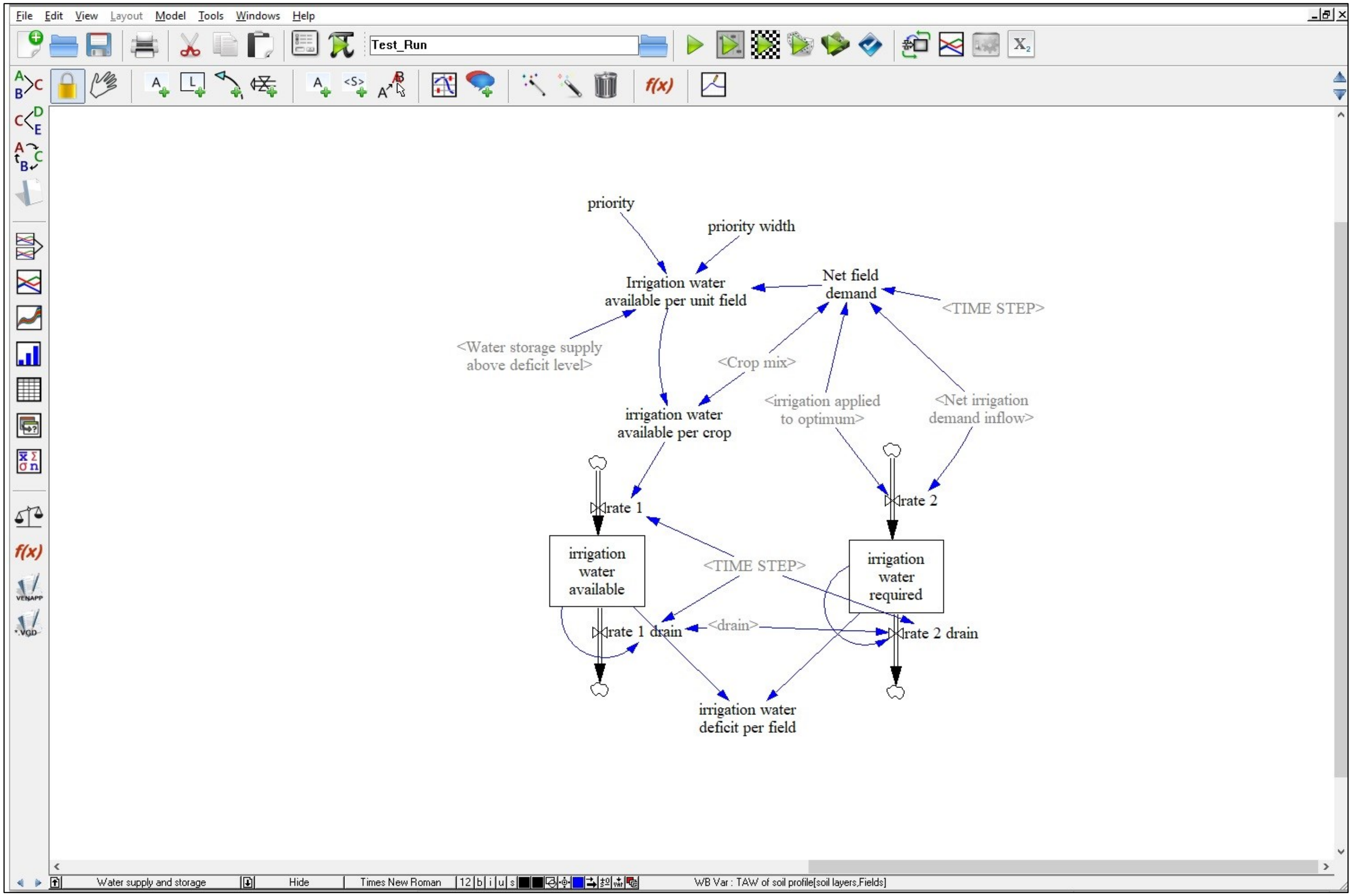


Figure A16. Water allocation between crops

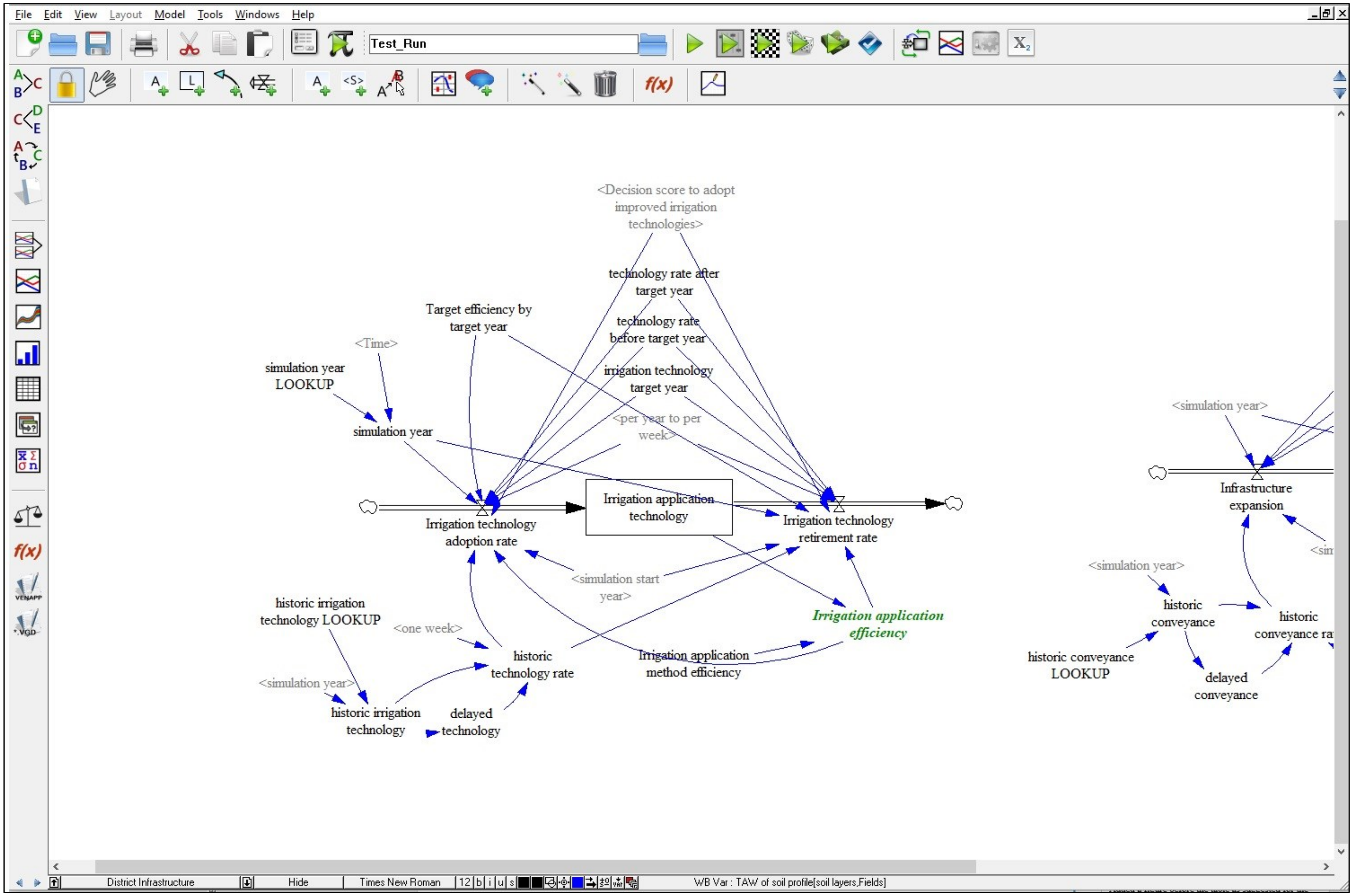


Figure A17. Irrigation application technology

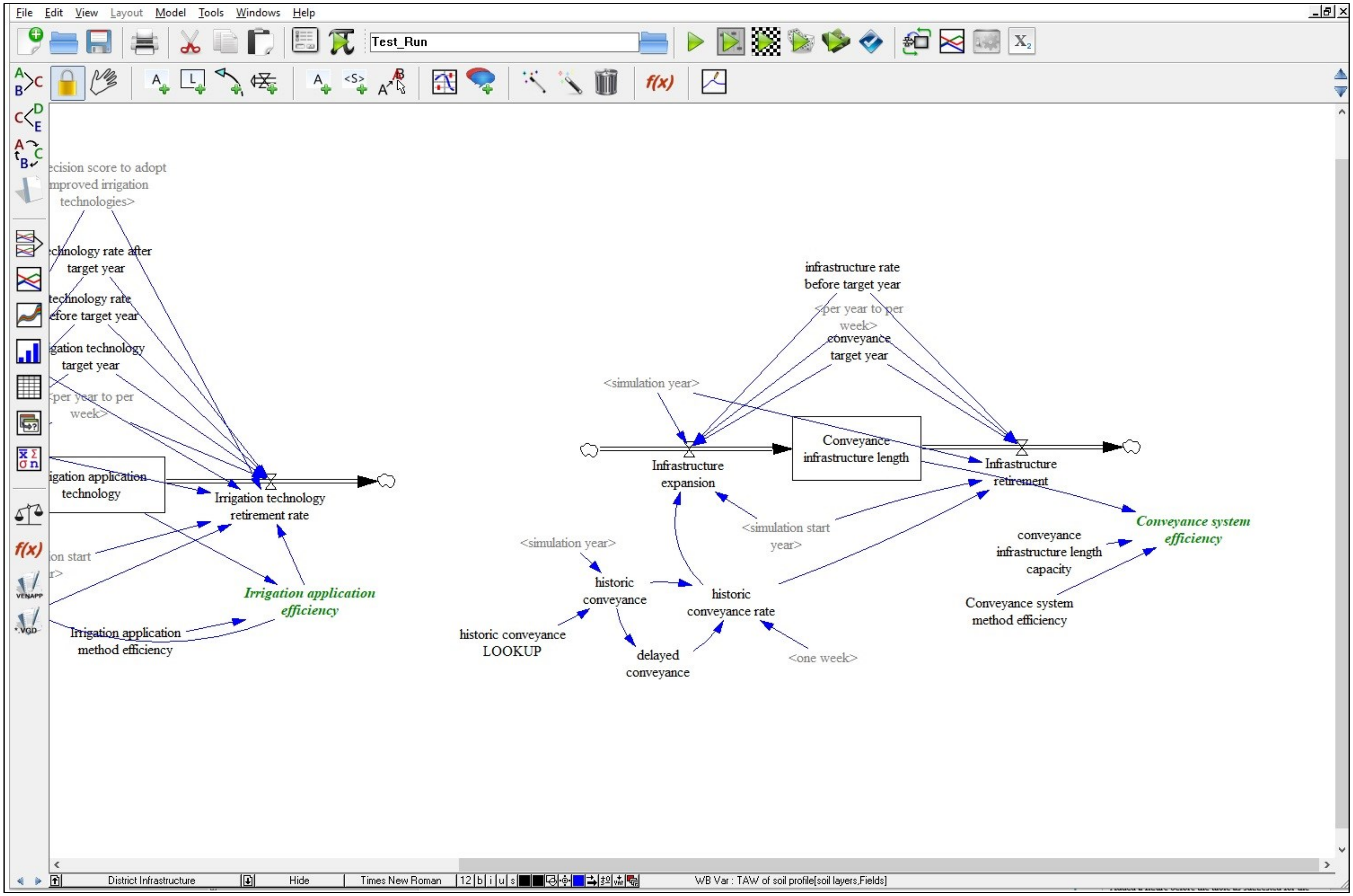


Figure A18. Conveyance infrastructure

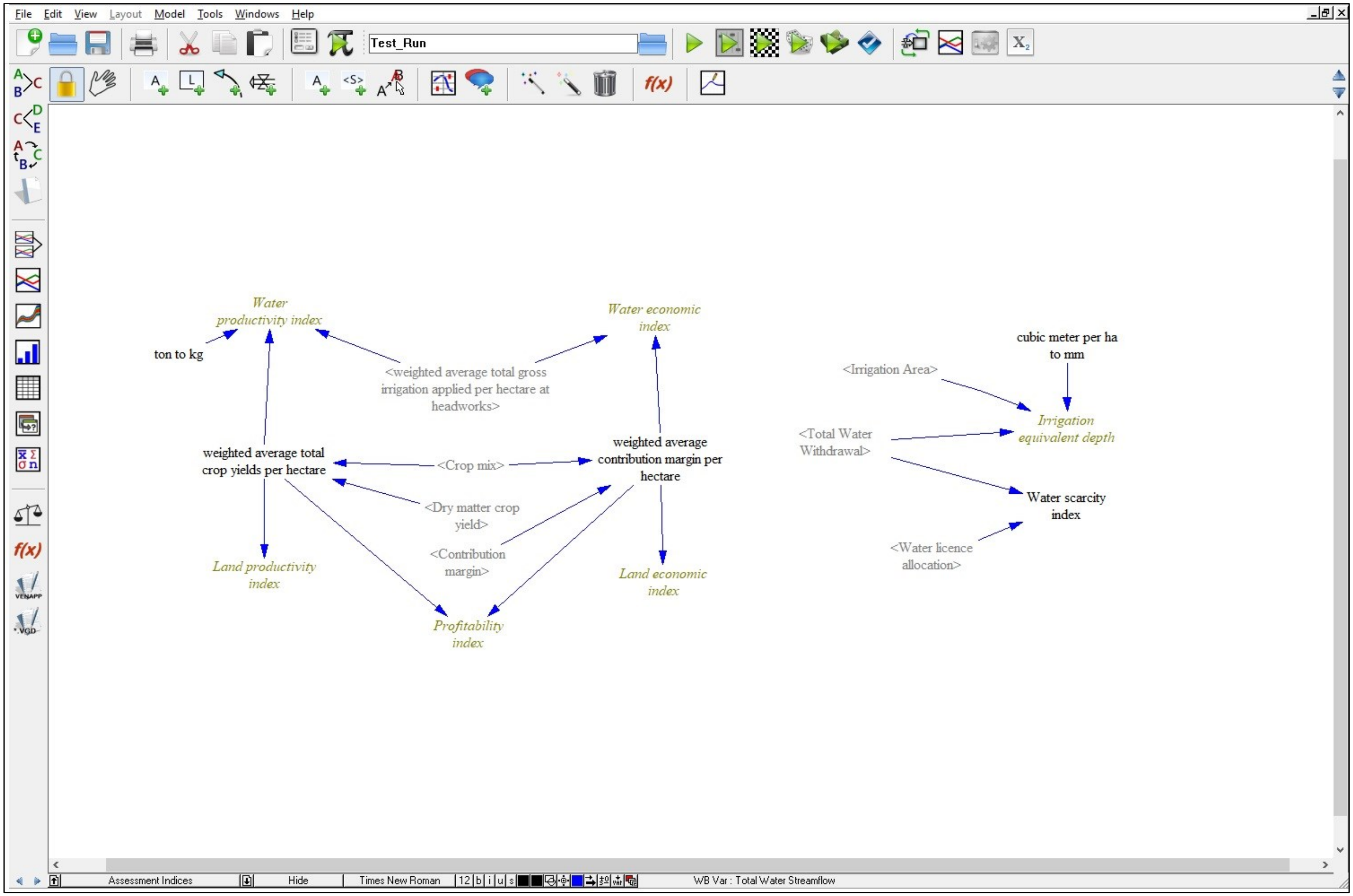


Figure A19. Model assessment indices

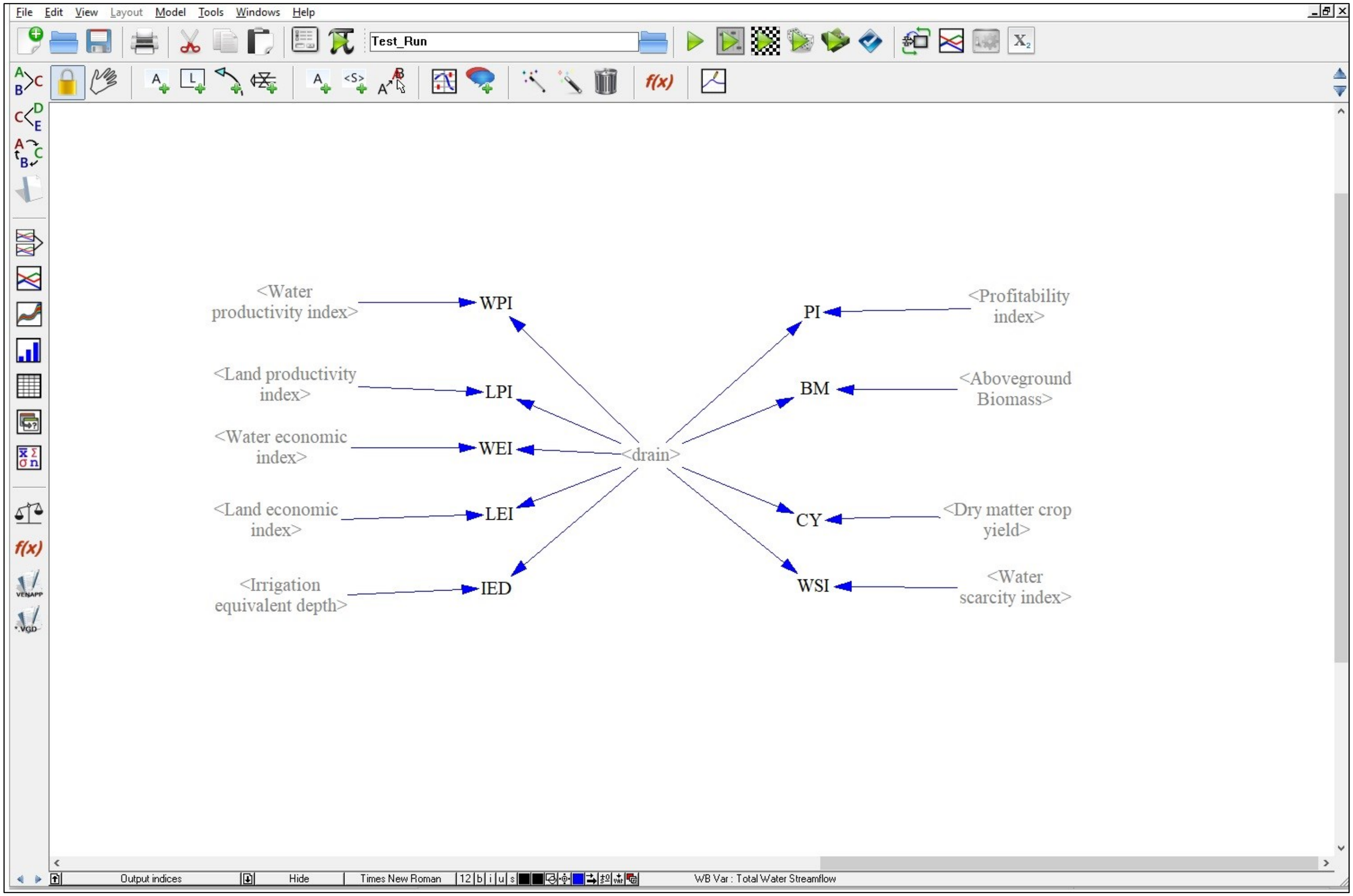


Figure A20. Model aggregated output

Table A1. The different views in AISS and the associated model component

View name	**Related model component**	**Brief description**	**Model structure and variables**
Reference evapotranspiration	Weather data inputs	This view shows the weather input model component which uses the climate inputs to calculate the reference evapotranspiration using four methods as described in Chapter 2 and Appendix B. In brief, the model offers four other temperature- and radiation-based methods with lower data requirements including three regression models by developed by Maulé et al. (2006), and the Priestly-Taylor equation (Priestley and Taylor, 1972). It also calculates the growing degree days which the model uses to progress the crop growth and development.	Figure A4
Soil water balance	CropSD	This view shows the sub-component that calculates the soil water dynamics. It uses the variables from other sub-components to simulate the change in the soil water content. Variables include evaporation, transpiration, drainage, deep percolation, redistribution of water between soil layers, soil profile water content, root zone depletion, and irrigation. Description of this component is provided in Chapter 2 and Appendix B: Supplementary Material for Chapter 2.	Figure A5
Canopy cover and rooting depth development	CropSD	This view shows the sub-component that simulates the development of the canopy cover with respect to the growing degree days. The model uses the growing degree days as the thermal clock for simulating the crop canopy development, but the results are shown in terms of time, the typical unit for system dynamics simulations. It also computes the accumulation of the growing degree days from sowing to emergence, sowing to transplanting, sowing to flowering, sowing to senescence.	Figure A6 and Figure A7

		The root zone development of the various crops is also simulated here as the effective rooting depth using the same approaches employed by AquaCrop as discussed in Chapter 2 and Appendix B: Supplementary Material for Chapter 2.	
Crop Yield Formation	Crop SD	This view shows the sub-component that simulates the aboveground biomass and crop yields for the six major crops of Alberta as modeled in Chapter 4 including alfalfa, barley, canola, potatoes, sugar beets, and wheat. The model has three main central variables namely, the harvest index, the accumulation of the aboveground biomass, and the estimation of the crop yield from the biomass and the harvest index. The effects of the increased CO_2 concentration are also simulated in that specific view based on the approaches employed by AquaCrop (refer to the model description in section 4.4 of Chapter 4). Effects of fertilizers on crop yields are also modeled using empirical relationships between crop yields and fertilizer applications for the crops grown in Alberta, as provided by McKenzie et al. (2013, 2004).	Figure A8
Stress response coefficients	CropSD	This view shows the model sub-component that calculates the water and temperature stress coefficients that affect the growth of the six crops simulated by the model. Three water stresses and one temperature stress are considered in the model following the approach by AquaCrop. For more information see the discussions in Chapter 2, Appendix B, and section 2.2 in Appendix D.	Figure A9
Irrigation area and crop mix	Water Demand, Supply, and Storage	This view shows the model sub-component that simulates the changes in both the irrigation area and the crop mix.	Figure A10
Water demand	Water demand, Supply, and Storage	This view includes the model component that simulates both the crop water requirements and the actual water applied for each crop during the	Figure A11 and Figure A12

		growing season in terms of depth of water. The crop water requirements are based on the soil moisture simulations and the allowable depletion as determined by the user inputs. The upscaling from the field scale calculations to the basin scale is achieved by multiplying the total water applied for each crop by the total area of each crop. The same model component also calculates the on-farm irrigation water requirements based on the irrigation application efficiencies. Then, it derives the total gross irrigation water demand at the head-works from the on-farm requirement, after accounting for water losses through the conveyance infrastructure (seepage and evaporation). Further description is provided in section 4.4.2.3 of Chapter 4.	
District Infrastructure	Irrigation Infrastructure	This view shows the model component that simulates the changes in the irrigation application technologies and the changes in the conveyance infrastructure length. Irrigation application technologies are low pressure center pivots, high pressure center pivots, wheelmove systems, gravity, and a “new technology” to account for advances in irrigation technologies including, for example, drip irrigation and variable rate irrigation systems. Conveyance infrastructure are pipelines, lined canals, and earth canals.	Figure A17 and Figure A18
Water supply and storage	Demand, Supply, Storage	This view shows the model sub-component that handles the water supply inputs to the model, and also simulates the storage changes during the growing season based on the water requirements simulated by the model. The storage is presented in terms of a single total live storage value for the irrigation sector; it includes both the reservoirs owned by the province of Alberta used for irrigation purposes and those owned by the irrigation districts of Alberta.	Figure A16 and Figure A15

Production Economics	Production Economics	This view shows the model component that simulates both the change in the crop production costs and revenues. The production costs are based on variable and non-variable water costs as described in section 2.2 in Chapter 4. The component simulates the changes in the energy required to pump for water delivery based on the actual amount of irrigation water requirements at the farm gate, as calculated in the crop growth component. Energy costs reflect the fractions of electricity and natural gas-based pumping systems in Alberta. Pumping hours are calculated from the pivot size, pivot flow rates, overall pump efficiency, and the pump operating pressure.	Figure A13
Socio-economic factor	Socio-economic Responses	This view shows the model component that simulates the responses of the irrigation community to changes in extension service, incentives to adopt new technologies, water supply conditions and demand risks, relative productivity and profitability of irrigation to dryland, and the aridity index as the ratio between the precipitation to the evapotranspiration. The response functions and the values of the lower and upper boundaries of the response functions are provided in section 4.4.2.5 of Chapter 4. Two decision scores are derived from the response functions that affect the rate of change in the irrigation area and the rate of adoption of new irrigation technologies to reflect the changes in irrigators' behavior towards risk. More description is provided in both Chapter 4 and Appendix D: Supplementary Material of Chapter 4.	Figure A14
Assessment Indices	Outputs	This view shows the assessment indices that the model calculates including: • Water productivity index: total crop production divided by total water withdrawal	Figure A19

		• Land productivity index: total crop production divided by total irrigation area • Water economic index: total economic returns divided by total water withdrawal • Land economic index: total crop production divided by total irrigation area • Water scarcity index: total irrigation water withdrawal divided by the total irrigation license • Irrigation equivalent depth: total irrigation water withdrawal divided by total irrigation area • Profitability index: total economic returns divided by total crop production	
Output Indices	Outputs	In this view, the model presents the final aggregated output of several assessment indices as described in section 4.6.2 of Chapter 4. The indices are aggregated to represent one value for each simulation year (i.e. growing season). The indices include the water productivity index, the land productivity index, the water security index, water economic index, land economic index, irrigation equivalent depth, and the profitability index.	Figure A20
Policy Control	AISS: Policy Experimentation	This view presents the control room for adjusting the model parameters using sliders to test the different policy interventions. It includes changing the storage, the rate of adoption of the different irrigation technologies, the rate of changing the conveyance infrastructure, the changes in the crop mix, the management of the irrigation, and the exogenous socio-economic factors (i.e., extension services and the incentives to adopt new technologies).	Figure A32

The aggregated model output variables are shown in Figure A20. They are aggregated for the growing season in order to show the changes from one year to the next as described in Table A1. The outputs are as follows:

- WPI: Water productivity index
- LPI: Land productivity index
- WEI: Water economic index
- LEI: Land economic index
- IED: Irrigation equivalent depth
- PI: Profitability index
- BM: Aboveground biomass
- CY: Crop yields
- WSI: Water scarcity index

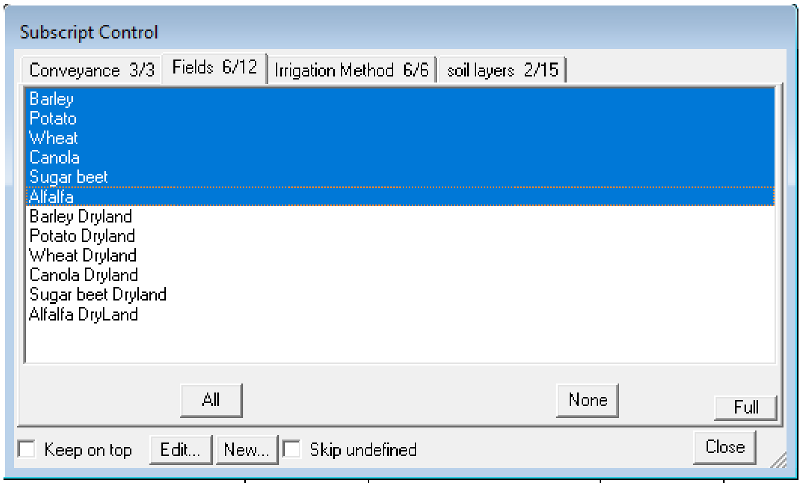
A2 Model Subscripts

AISS has four subscripts to describe arrays of soil layers, conveyance infrastructure, crops, and irrigation technologies. Subscripting in Vensim allows a reproduction of model structures, such that the stock and flow diagrams of the "views" can be made simpler and clearer, or can be used to provide multiple attributes to a single variable name. For instance, conveyance infrastructure could be represented as a single array with three subscripts for the three conveyance infrastructure types, pipelines, lined canals, and earth canals. In the most common syntax, the variable would be shown as *conveyance*[*type*], where *type* could be pipeline, lined canals, or earth canals. Variables can also have more than one array, such as a location and an infrastructure type, which is represented as *conveyance*[*district_name*][*type*]. The same applies to the irrigation technologies. Vensim's documentation explains,

> *"Often a piece of model structure will need to be repeated over and over again. For example, a retail store might be replicated for many different regions, or a factory production process might be repeated several times. One method for repeating structure is to create and debug one structure, then copy and replicate that structure as many times as needed. However, this can lead to complex diagrams and hard-wiring of constant values and number of structures. A better way to repeat structure is to use subscripts. A subscript is created and added to the one original structure, creating as many structures as there are subscript elements. Now numbers of structures and numerical values for all structures can easily be changed."* (URL: http://www.vensim.com/subscripting/, Last accessed: August 24, 2018)

The arrayed structure of the soil layers is discussed in Chapter 2 and its supporting material in Appendix B. In brief, the model has 15 soil layers at which water percolates from one layer to the next after a wetting event (i.e., irrigation event or rainfall event). The subscript for that array is named "soil layers" – see Figure A21.

AISS simulates crop yields of six crops as described in Table A1 for irrigated fields and the corresponding yield of drylands (by setting the value for irrigation depth to 0). This was needed to allow the model to calculate the relative productivity differences between irrigated land areas and corresponding drylands, which is then used for the calculations of the decision to expand irrigation areas, as discussed in Table A1. Therefore, the model simulates a total of twelve crop yields but only shows the crop yields corresponding to the irrigated fields by default. If the user wishes to show the crop yields of the corresponding dryland fields, they may click on the desired crop name in the “Subscript Control” window in Vensim as shown in Figure A21. The subscript is named “Fields” where each field describes one crop.



Barley
Potato
Wheat
Canola
Sugar beet
Alfalfa
Barley Dryland
Potato Dryland
Wheat Dryland
Canola Dryland
Sugar beet Dryland
Alfalfa DryLand

Figure A21. Subscripts Control window of Vensim showing the four arrays of AISS

A3 Model Assumptions

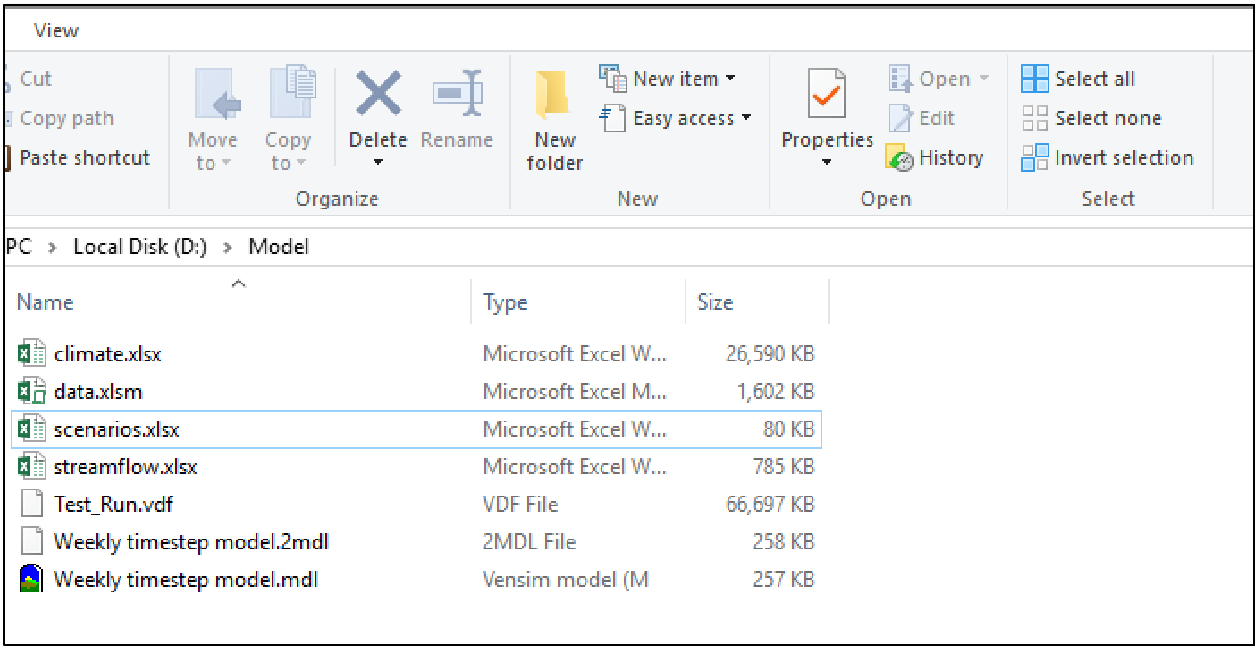
AISS assumes that each field has a different crop but similar key characteristics (e.g., soil properties, weather variability, or irrigation infrastructure improvements). Crop productions are spatially aggregated to estimate the total production by multiplying the crop yield of each field by the total area of the crop. The conceptualization of interactions of the different subsystems necessitate a degree of aggregation; otherwise, integration across different spatial scales is not possible (Kelly et al., 2013). It is worth noting that few crop growth models have been used for regional analysis that scales up from field scale to landscape and regional scales conceptually through aggregating production (Hansen and Jones, 2000), or through linking existing crop models with geographical information systems (GIS) packages (Balkovič et al., 2013; Nichols et al., 2011) (see Ewert et al. (2011) and citations therein for a critical discussion on scaling). Moreover, if the irrigation district expands or increases its expansion limit, it is assumed that each of the six fields increases by the same percentage. This method is a simplification of reality, because irrigation expansion depends on the availability of the land and its suitability for agriculture as well as its location relative to the irrigation infrastructure. This is one trade-off of aggregation into larger units for simulation in system dynamics, which could potentially be addressed using a spatiotemporal system dynamics approach that connects a temporal model to a GIS database.

The model assumes that the diffusion of the new irrigation application technologies is uniform across all irrigated land area – a necessity to upscale the model from the field scale to the basin scale. A general limitation of system dynamics modeling is the treatment of space and spatial heterogeneity. Similarly, AISS could benefit from disaggregating the different reservoirs for accurate evaporation area estimation and for incorporating individual reservoir operation rules.

A4 Model Inputs through Excel

MS Excel is used to store the data that Vensim imports for use by AISS model. The model folder has five main files: four Excel spreadsheets for the data input and scenario analysis that AISS model calls when a simulation is run, and one file for the model itself, which is in **.mdl* format as shown in Figure A22.

The MDL file format must be executed in Vensim DSS software.



PC > Local Disk (D:) > Model

Name	Type	Size
climate.xlsx	Microsoft Excel W...	26,590 KB
data.xlsm	Microsoft Excel M...	1,602 KB
scenarios.xlsx	Microsoft Excel W...	80 KB
streamflow.xlsx	Microsoft Excel W...	785 KB
Test_Run.vdf	VDF File	66,697 KB
Weekly timestep model.2mdl	2MDL File	258 KB
Weekly timestep model.mdl	Vensim model (M	257 KB

Figure A22. Model folder and typical four Excel input files

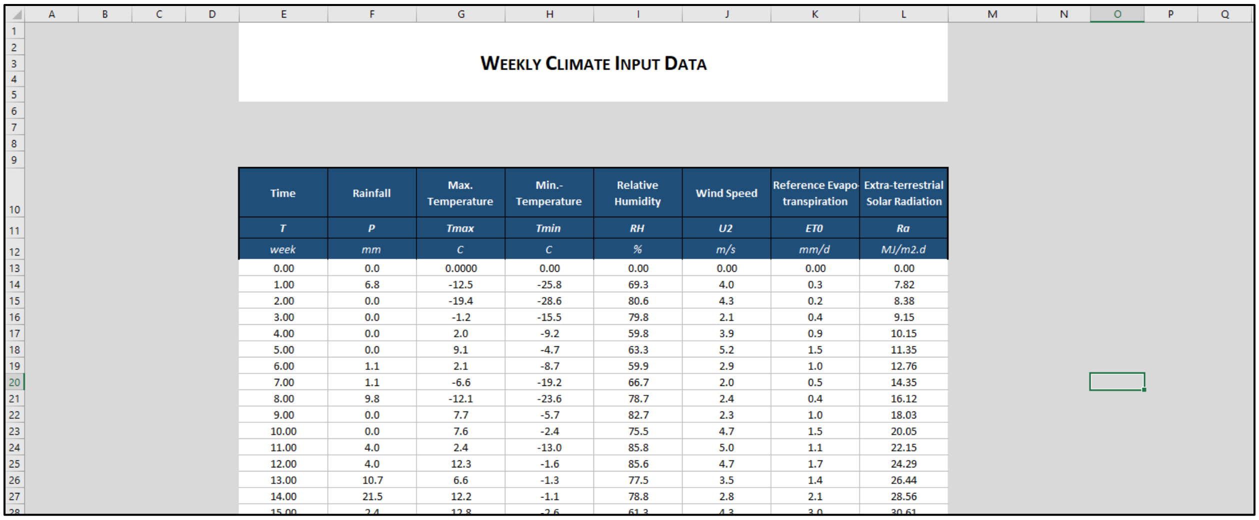
The four Excel spreadsheets include,

- Climate.xlsx
- Streamflow.xlsx
- Data.xlsm
- Scenarios.xlsx

“climate.xlsx”: This file has all the climate data needed to run the model – see Figure A23 and Figure A24. The file has two main Worksheets as follows: Climate, and Input Climate Data. AISS reads inputs from the “Climate” worksheet tab. While AISS uses aggregated weekly climate input data from “Climate”, users may choose to input the required data in one of two forms, namely daily or weekly weather data. The climate file has a time frame starting at 01-01-1993 and running to 31-12-2040, and is sorted by week number. Data imported to the Excel sheet, however, do not have to start from 1993 but can start at any time, so long as the simulation INITIAL TIME in Vensim DSS is adjusted to match the week at which the first climate input appears in the climate Excel sheet.

To use daily data, users paste the climate data in the “Input Climate Data” and then the Excel sheet aggregates the daily data into weekly values in the “Climate” worksheet. Otherwise, if the user wishes to use weekly data directly, then he/she may paste the data directly to the “Climate” worksheet. If taking this approach, note that calculations in the Excel spreadsheet will be overwritten. Therefore, it is recommended to create a backup of the file in order to keep the calculation of the aggregation valid for future uses or to create a copy of the “Climate” worksheet that contains all the original formulae.

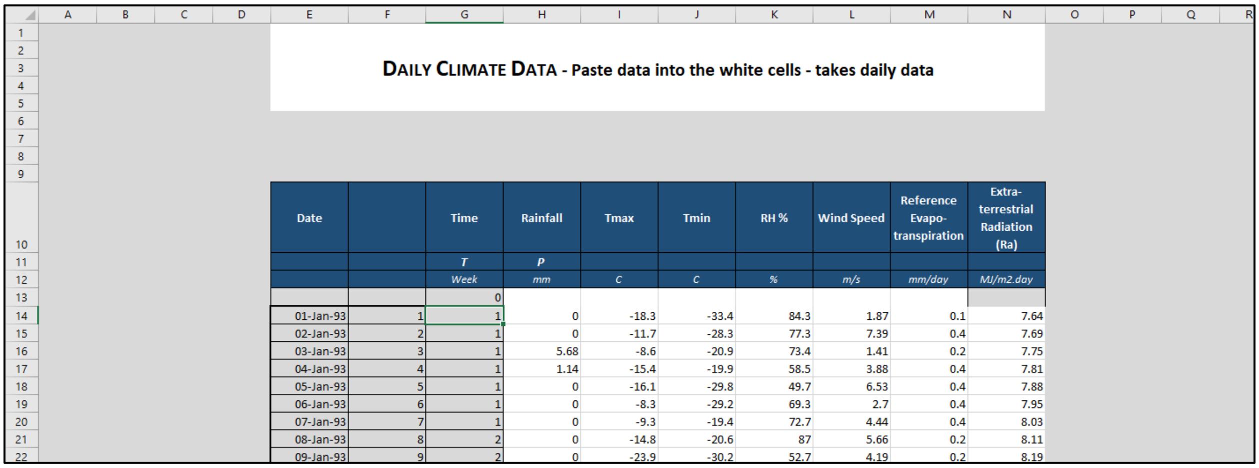
The required data for the model are the precipitation in millimeters, maximum temperature in degrees Celsius, minimum temperature in degrees Celsius, relative humidity in percentage, wind speed at 2 meters high in meters per second, the reference evapotranspiration in millimeters per day, and the extra-terrestrial solar radiation in megajoules per meter squared per day. If the reference evapotranspiration data are not readily available, the user could use instead one of the four methods provided by the model to calculate the reference evapotranspiration as described in Table A1. However, the column of the reference evapotranspiration should not be left blank, as the model will still import the values but will not use them in the simulation.



WEEKLY CLIMATE INPUT DATA

Time	Rainfall	Max. Temperature	Min.- Temperature	Relative Humidity	Wind Speed	Reference Evapo-transpiration	Extra-terrestrial Solar Radiation
T	*P*	*Tmax*	*Tmin*	*RH*	*U2*	*ET0*	*Ra*
week	*mm*	*C*	*C*	*%*	*m/s*	*mm/d*	*MJ/m2.d*
0.00	0.0	0.0000	0.00	0.00	0.00	0.00	0.00
1.00	6.8	-12.5	-25.8	69.3	4.0	0.3	7.82
2.00	0.0	-19.4	-28.6	80.6	4.3	0.2	8.38
3.00	0.0	-1.2	-15.5	79.8	2.1	0.4	9.15
4.00	0.0	2.0	-9.2	59.8	3.9	0.9	10.15
5.00	0.0	9.1	-4.7	63.3	5.2	1.5	11.35
6.00	1.1	2.1	-8.7	59.9	2.9	1.0	12.76
7.00	1.1	-6.6	-19.2	66.7	2.0	0.5	14.35
8.00	9.8	-12.1	-23.6	78.7	2.4	0.4	16.12
9.00	0.0	7.7	-5.7	82.7	2.3	1.0	18.03
10.00	0.0	7.6	-2.4	75.5	4.7	1.5	20.05
11.00	4.0	2.4	-13.0	85.8	5.0	1.1	22.15
12.00	4.0	12.3	-1.6	85.6	4.7	1.7	24.29
13.00	10.7	6.6	-1.3	77.5	3.5	1.4	26.44
14.00	21.5	12.2	-1.1	78.8	2.8	2.1	28.56
15.00	2.4	12.8	-2.6	61.3	4.3	3.0	30.61

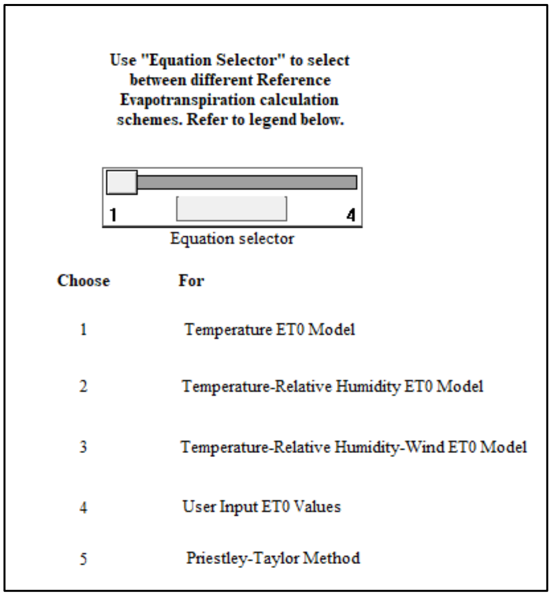
Figure A23. Weekly worksheet of "*climate.xlsx*" Excel input file



DAILY CLIMATE DATA - Paste data into the white cells - takes daily data

Date		Time	Rainfall	Tmax	Tmin	RH %	Wind Speed	Reference Evapo-transpiration	Extra-terrestrial Radiation (Ra)
		T	*P*						
		Week	*mm*	*C*	*C*	*%*	*m/s*	*mm/day*	*MJ/m2.day*
		0							
01-Jan-93	1	1	0	-18.3	-33.4	84.3	1.87	0.1	7.64
02-Jan-93	2	1	0	-11.7	-28.3	77.3	7.39	0.4	7.69
03-Jan-93	3	1	5.68	-8.6	-20.9	73.4	1.41	0.2	7.75
04-Jan-93	4	1	1.14	-15.4	-19.9	58.5	3.88	0.4	7.81
05-Jan-93	5	1	0	-16.1	-29.8	49.7	6.53	0.4	7.88
06-Jan-93	6	1	0	-8.3	-29.2	69.3	2.7	0.4	7.95
07-Jan-93	7	1	0	-9.3	-19.4	72.7	4.44	0.4	8.03
08-Jan-93	8	2	0	-14.8	-20.6	87	5.66	0.2	8.11
09-Jan-93	9	2	0	-23.9	-30.2	52.7	4.19	0.2	8.19

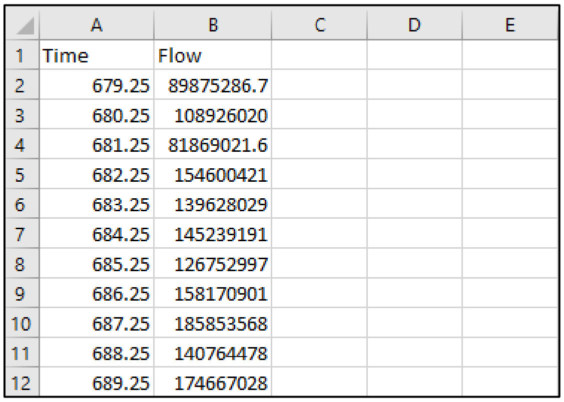
Figure A24. Daily worksheet of "*climate.xlsx*" Excel input file



Use "Equation Selector" to select between different Reference Evapotranspiration calculation schemes. Refer to legend below.

Choose	**For**
1	Temperature ET0 Model
2	Temperature-Relative Humidity ET0 Model
3	Temperature-Relative Humidity-Wind ET0 Model
4	User Input ET0 Values
5	Priestley-Taylor Method

Figure A25. Choice of the reference evapotranspiration calculation method using the slider available in the Reference Evapotranspiration view of AISS “***streamflow.xlsx***”: This spreadsheet has the simulated streamflow data that serve as the water supply for the irrigation sector. The data are in cubic meters per day. Because AISS reads the inputs from the “Streamflow” tab, it is important not to change the name of the tab or the order of the input data. Two columns describe the data: “Time” and “Flow”. Time is in weeks starting from the week number that corresponds to the INITIAL TIME of AISS in Vensim – see Figure A26. Flow is the total river flow over one week, represented as cubic meters per day. In the figure below, the flow data are from the hydrological model, SWAT.



	A	B	C	D	E
1	Time	Flow			
2	679.25	89875286.7			
3	680.25	108926020			
4	681.25	81869021.6			
5	682.25	154600421			
6	683.25	139628029			
7	684.25	145239191			
8	685.25	126752997			
9	686.25	158170901			
10	687.25	185853568			
11	688.25	140764478			
12	689.25	174667028			

Figure A26. Streamflow worksheet of “*streamflow.xlsx*” Excel spreadsheet

“***data.xlsm***”: This spreadsheet has other inputs required for AISS to complete a simulation. The inputs include:

- Crop parameters,
- Crop production costs and selling prices,
- Storage capacity,
- Efficiencies of the five irrigation application technologies
- Efficiencies of the of conveyance infrastructure, and
- Response functions of the socioeconomic component

The spreadsheet has four main worksheets that describe all the inputs for the model. These worksheets are “Control Sheet”, “CropData”, “Economics”, “IrrigTechFn”, “constants”, and “cropprice”.

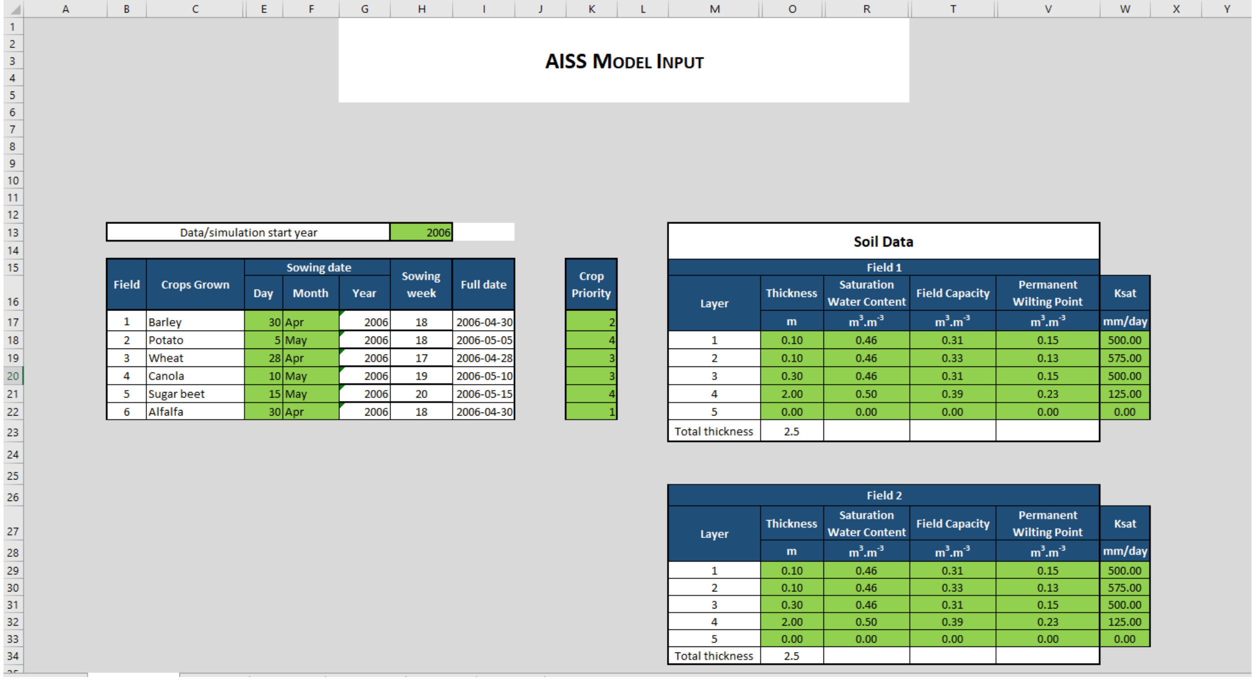
Note that “*data.xlsm*” is a Macro-Enable workbook to allow future expansion of the capabilities of AISS to incorporate optimization routines for changing dynamically the crop mix using means of coding in Visual Basic for Applications (VBA).

data.xlsm -> *Control Sheet*

This worksheet specifies the sowing date for each of the six crops simulated by the model, and the soil layer properties for each of the six fields on which the crops grow. The crops include barley, potatoes, canola, wheat, sugar beets, and alfalfa. Sowing date is specified in terms of the month and day. The year can be changed using the *simulation start year* cell as shown in Figure A27. In general, only the green cells are to be changed if needed.

The worksheet also specifies the soil layer properties for each of the six fields of the six different crops. There can be up to 5 distinct layers with different thickness and soil properties. Each layer for each field reads the thickness in meters, the saturation water content ratio, field capacity water content ratio, permanent wilting point ratio, and the saturation hydraulic conductivity in millimeters per day.

Note that the order of the crops in the Excel spreadsheet must remain unchanged as Barley, Potatoes, Wheat, Canola, Sugar beets, and Alfalfa.



AISS MODEL INPUT

Data/simulation start year	2006

Field	Crops Grown	Sowing date			Sowing week	Full date
		Day	Month	Year		
1	Barley	30	Apr	2006	18	2006-04-30
2	Potato	5	May	2006	18	2006-05-05
3	Wheat	28	Apr	2006	17	2006-04-28
4	Canola	10	May	2006	19	2006-05-10
5	Sugar beet	15	May	2006	20	2006-05-15
6	Alfalfa	30	Apr	2006	18	2006-04-30

Crop Priority
2
4
3
3
4
1

Soil Data

Field 1

Layer	Thickness	Saturation Water Content	Field Capacity	Permanent Wilting Point	Ksat
	m	$m^3.m^{-3}$	$m^3.m^{-3}$	$m^3.m^{-3}$	mm/day
1	0.10	0.46	0.31	0.15	500.00
2	0.10	0.46	0.33	0.13	575.00
3	0.30	0.46	0.31	0.15	500.00
4	2.00	0.50	0.39	0.23	125.00
5	0.00	0.00	0.00	0.00	0.00
Total thickness	2.5				

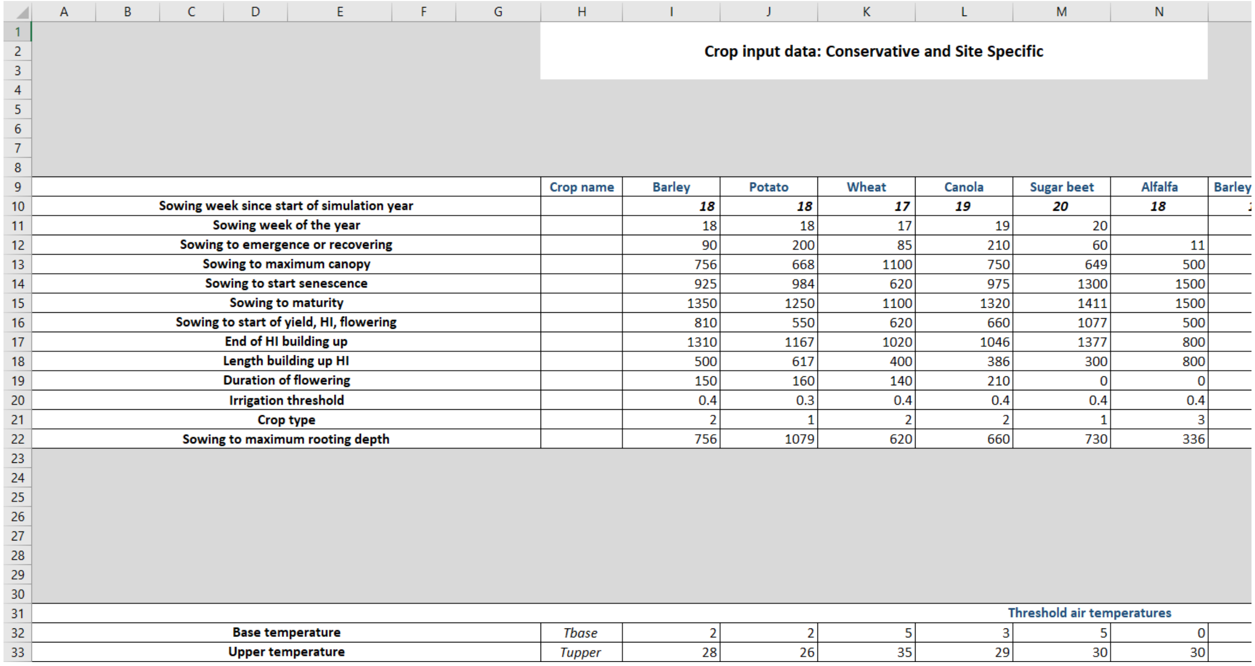
Field 2

Layer	Thickness	Saturation Water Content	Field Capacity	Permanent Wilting Point	Ksat
	m	$m^3.m^{-3}$	$m^3.m^{-3}$	$m^3.m^{-3}$	mm/day
1	0.10	0.46	0.31	0.15	500.00
2	0.10	0.46	0.33	0.13	575.00
3	0.30	0.46	0.31	0.15	500.00
4	2.00	0.50	0.39	0.23	125.00
5	0.00	0.00	0.00	0.00	0.00
Total thickness	2.5				

Figure A27. *Control Sheet* worksheet for the "*data.xslm*" spreadsheet

data.xlsm -> *CropData*

The input data in the *CropData* worksheet include both the conservative (constant for a crop variety) and the site-specific crop parameters. A snapshot of the worksheet is shown in Figure A28. The crop parameters are the growing degree days for each growth stage starting with sowing: root zone development parameters, growth threshold air temperatures, crop canopy development parameters, crop transpiration parameters, aboveground biomass and crop yield formation parameters, air temperature stresses and water stresses parameters, the agronomic response of crops to soil nutrients parameters. Sources for the crop parameters obtained for the six modeled crops for southern Alberta are provided in Chapter 4.



Crop input data: Conservative and Site Specific

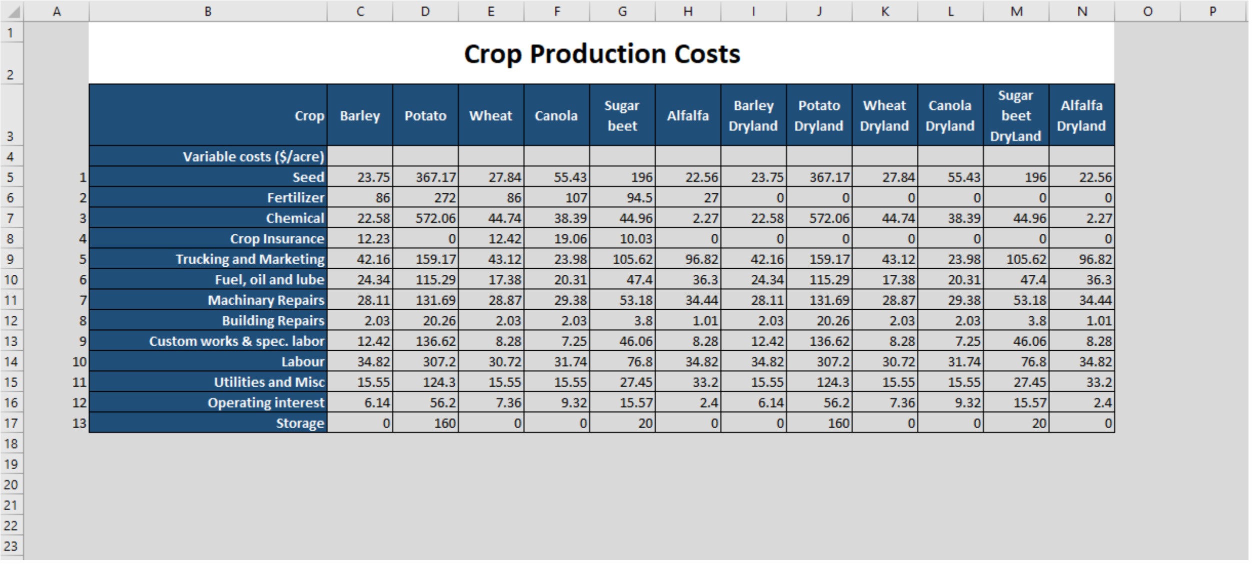
	Crop name	Barley	Potato	Wheat	Canola	Sugar beet	Alfalfa	Barley
Sowing week since start of simulation year		***18***	***18***	***17***	***19***	***20***	***18***	
Sowing week of the year		18	18	17	19	20		
Sowing to emergence or recovering		90	200	85	210	60	11	
Sowing to maximum canopy		756	668	1100	750	649	500	
Sowing to start senescence		925	984	620	975	1300	1500	
Sowing to maturity		1350	1250	1100	1320	1411	1500	
Sowing to start of yield, HI, flowering		810	550	620	660	1077	500	
End of HI building up		1310	1167	1020	1046	1377	800	
Length building up HI		500	617	400	386	300	800	
Duration of flowering		150	160	140	210	0	0	
Irrigation threshold		0.4	0.3	0.4	0.4	0.4	0.4	
Crop type		2	1	2	2	1	3	
Sowing to maximum rooting depth		756	1079	620	660	730	336	

					Threshold air temperatures			
Base temperature	*Tbase*	2	2	5	3	5	0	
Upper temperature	*Tupper*	28	26	35	29	30	30	

Figure A28. *CropData* worksheet for the "*data.xslm*" spreadsheet

data.xlsm *-> Economics*

The *Economics* worksheet includes the cost of production for each of the six crops on both irrigated land and rainfed land – see Figure A29. The rainfed data is required for the calculation of the relative profitability between irrigated land and drylands as described in Chapter 4. The production costs are for 13 different categories and are in nominal Canadian dollars per unit acre of land. Data sources are described in Chapter 4. The different categories are: cost of seeds, fertilizers, chemicals, crop insurance, trucking and marketing, fuel, oil and lube, machinery repairs, labor, utilities, operating interest, and storage.



Crop Production Costs

	Crop	Barley	Potato	Wheat	Canola	Sugar beet	Alfalfa	Barley Dryland	Potato Dryland	Wheat Dryland	Canola Dryland	Sugar beet DryLand	Alfalfa Dryland
	Variable costs ($/acre)												
1	Seed	23.75	367.17	27.84	55.43	196	22.56	23.75	367.17	27.84	55.43	196	22.56
2	Fertilizer	86	272	86	107	94.5	27	0	0	0	0	0	0
3	Chemical	22.58	572.06	44.74	38.39	44.96	2.27	22.58	572.06	44.74	38.39	44.96	2.27
4	Crop Insurance	12.23	0	12.42	19.06	10.03	0	0	0	0	0	0	0
5	Trucking and Marketing	42.16	159.17	43.12	23.98	105.62	96.82	42.16	159.17	43.12	23.98	105.62	96.82
6	Fuel, oil and lube	24.34	115.29	17.38	20.31	47.4	36.3	24.34	115.29	17.38	20.31	47.4	36.3
7	Machinary Repairs	28.11	131.69	28.87	29.38	53.18	34.44	28.11	131.69	28.87	29.38	53.18	34.44
8	Building Repairs	2.03	20.26	2.03	2.03	3.8	1.01	2.03	20.26	2.03	2.03	3.8	1.01
9	Custom works & spec. labor	12.42	136.62	8.28	7.25	46.06	8.28	12.42	136.62	8.28	7.25	46.06	8.28
10	Labour	34.82	307.2	30.72	31.74	76.8	34.82	34.82	307.2	30.72	31.74	76.8	34.82
11	Utilities and Misc	15.55	124.3	15.55	15.55	27.45	33.2	15.55	124.3	15.55	15.55	27.45	33.2
12	Operating interest	6.14	56.2	7.36	9.32	15.57	2.4	6.14	56.2	7.36	9.32	15.57	2.4
13	Storage	0	160	0	0	20	0	0	160	0	0	20	0

Figure A29. *Economics* worksheet for the "*data.xslm*" spreadsheet

data.xlsm -> *IrrigTechFn*

This worksheet includes the response functions for the socioeconomic component of the model as described in Chapter 4. The response functions for the five Likert scales that contribute to the decision to adopt irrigation technologies and the decision to expand irrigation area are described by a logistic function. Four of the five scales contribute to the decision by irrigators to adopt irrigation technologies, namely the water demand index, the extension services, access to incentives, and productivity and profitability index. Three of the five scales contribute to the decision by the irrigation community to expand the irrigated land areas, namely the aridity index, the water demand risk, and the productivity and profitability index. Note that a detailed sensitivity analysis for the different weightings of each scale should be conducted in future work, as well as the model sensitivity to changes in the response functions of the different scales.

To describe how the decision scores are simulated work, consider the case of the decision score on irrigation land areas. The score changes the rate of expansion of the irrigation area, which affects the growth of the irrigated area directly, through the following equation:

$$\frac{dI}{dt} = \left(\theta_{exp} \cdot r_{base}\right) \tag{A1}$$

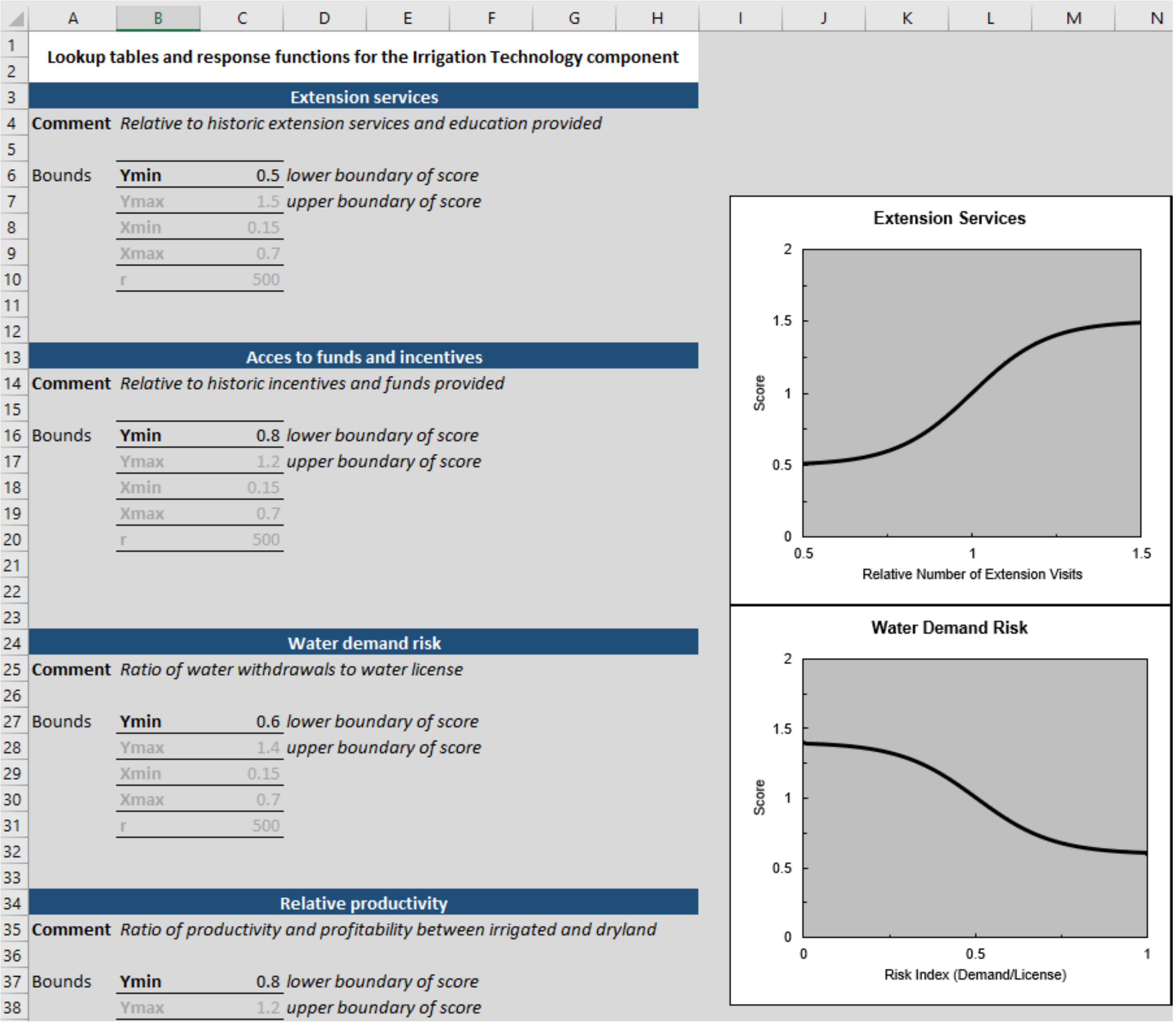
where dI/dt is the rate of expansion in the irrigated area (ha yr^{-1}), θ_{exp} is the decision score to expand the irrigated land areas represented as a multiplier simulated endogenously, r_{base} is the base expansion rate (fraction yr^{-1}).

The decision score θ_{exp} is simulated using the following equation:

$$\theta_{exp} = \frac{1}{n}\sum_{i=1}^{n} \alpha_i \times S_i \tag{A2}$$

where n is the number of the scales that contribute to the decision, α_i is the weighting factor of scale i, and S_i is the response value of scale i.

The response of the different scales can be changed by adjusting the constants of the logistic function. For example, the upper and lower boundary for the score can be altered by changing the values of the *Ymin* for each of the five scales while *Ymax* will be changed automatically. The steepness of the S-shaped curve can be adjusted using the value that corresponds to the *r* cell as shown in Figure A30.



	A	B	C	D
1	**Lookup tables and response functions for the Irrigation Technology component**			
3	**Extension services**			
4	**Comment**	*Relative to historic extension services and education provided*		
6	Bounds	**Ymin**	0.5	*lower boundary of score*
7		Ymax	1.5	*upper boundary of score*
8		Xmin	0.15	
9		Xmax	0.7	
10		r	500	
13	**Acces to funds and incentives**			
14	**Comment**	*Relative to historic incentives and funds provided*		
16	Bounds	**Ymin**	0.8	*lower boundary of score*
17		Ymax	1.2	*upper boundary of score*
18		Xmin	0.15	
19		Xmax	0.7	
20		r	500	
24	**Water demand risk**			
25	**Comment**	*Ratio of water withdrawals to water license*		
27	Bounds	**Ymin**	0.6	*lower boundary of score*
28		Ymax	1.4	*upper boundary of score*
29		Xmin	0.15	
30		Xmax	0.7	
31		r	500	
34	**Relative productivity**			
35	**Comment**	*Ratio of productivity and profitability between irrigated and dryland*		
37	Bounds	**Ymin**	0.8	*lower boundary of score*
38		Ymax	1.2	*upper boundary of score*

Figure A30 IrrigTechFn worksheet for the "*data.xslm*" spreadsheet

data.xlsm -> *Constants*

The *Constants* worksheet has the reservoir storage capacity of the irrigation sector. It also has the application efficiency for the five irrigation application technologies included in AISS – see the discussion of application technologies in Chapter 4. The efficiencies of the different conveyance infrastructure types can also be adjusted in this worksheet.

data.xlsm -> *CropPrice*

The *CropPrice* worksheet includes the expected crop selling price for Alberta for each year of the simulation period. Values are provided for the six irrigated crops and the corresponding six rainfed crops.

*"**scenarios.xlsx**":* This file is used to set up the different scenario experiments to analyze the expansion scenarios, the crop mix changes, the climate scenarios, and the policy interventions.

There are four main expansion scenarios as discussed in Chapter 4: stagnation, slow development, as-planned expansion, and rapid (significant expansion) development. An expansion scenario is represented in the model as the "rate of expansion" in hectares per year. The value can be changed based on one of the four preset values or through user input. The model allows two time periods with two different expansion scenarios if required. The user specifies the year that separates the two periods and assign different rates for each period. For example, assume that the Government of Alberta specified a rate of expansion of 3000 hectares per year for the next 10 years, and then 2000 hectares per year for the five year after. The user would specify the date starting from 2018 to be 2028 and then choose 3000 hectares per year for the first time period and 2000 for the last time period.

The crop mix changes are represented in terms of the rate of changes in the crop mix percentages from 2018 to 2040 (end of the simulation period). Four scenarios are preset in the Excel sheet as described in Chapter 4. These include water conservation crop mix, current crop mix, water-intensive crop mix, and high-value crop mix.

A5 Running the Model

There are two options for setting up the scenarios for AISS: (1) using the Excel spreadsheet, and (2) using the *Policy Control* view of the model in Vensim. Figure A32 shows a snapshot of the *Policy Control* view of the model. The control screen uses model sliders than can allow altering the values by pressing and dragging the slider to the desired value. It is enabled through running the model in SyntheSim mode.

Basically, a simulation can be run in Vensim can be through: (1) "what-if" runs where the parameters are changed using the Excel sheets or using Vensim Equation Editor (see Vensim documentation at: https://www.vensim.com/documentation/index.html?vensim_help.htm), (2) SyntheSim, where Vensim presents the results of simulations superimposed on the model diagrams and instantly updates these displays as the user changes model parameters, and (3) Monte Carlo simulations for investigating the sensitivity of the model to certain variables as set by the user – see Figure A31

It is worth noting that the model takes a couple of seconds to finish one simulation. Therefore, changing each slider at a time in SyntheSim will take a fraction of a minute to complete.

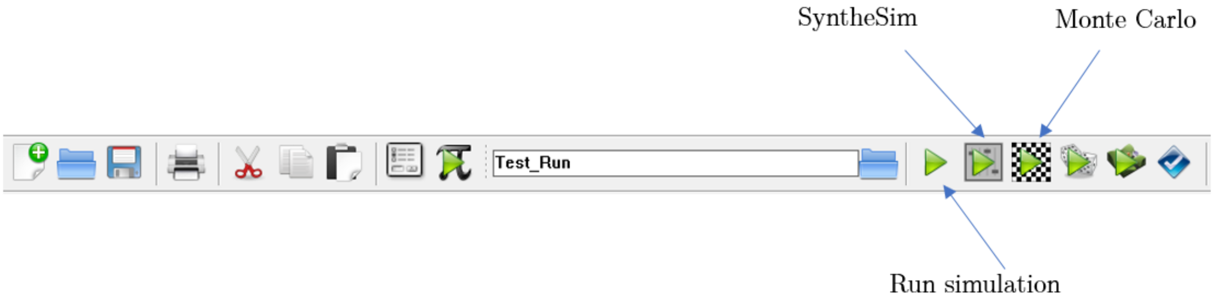


Figure A31. How to run a simulation in Vensim DSS

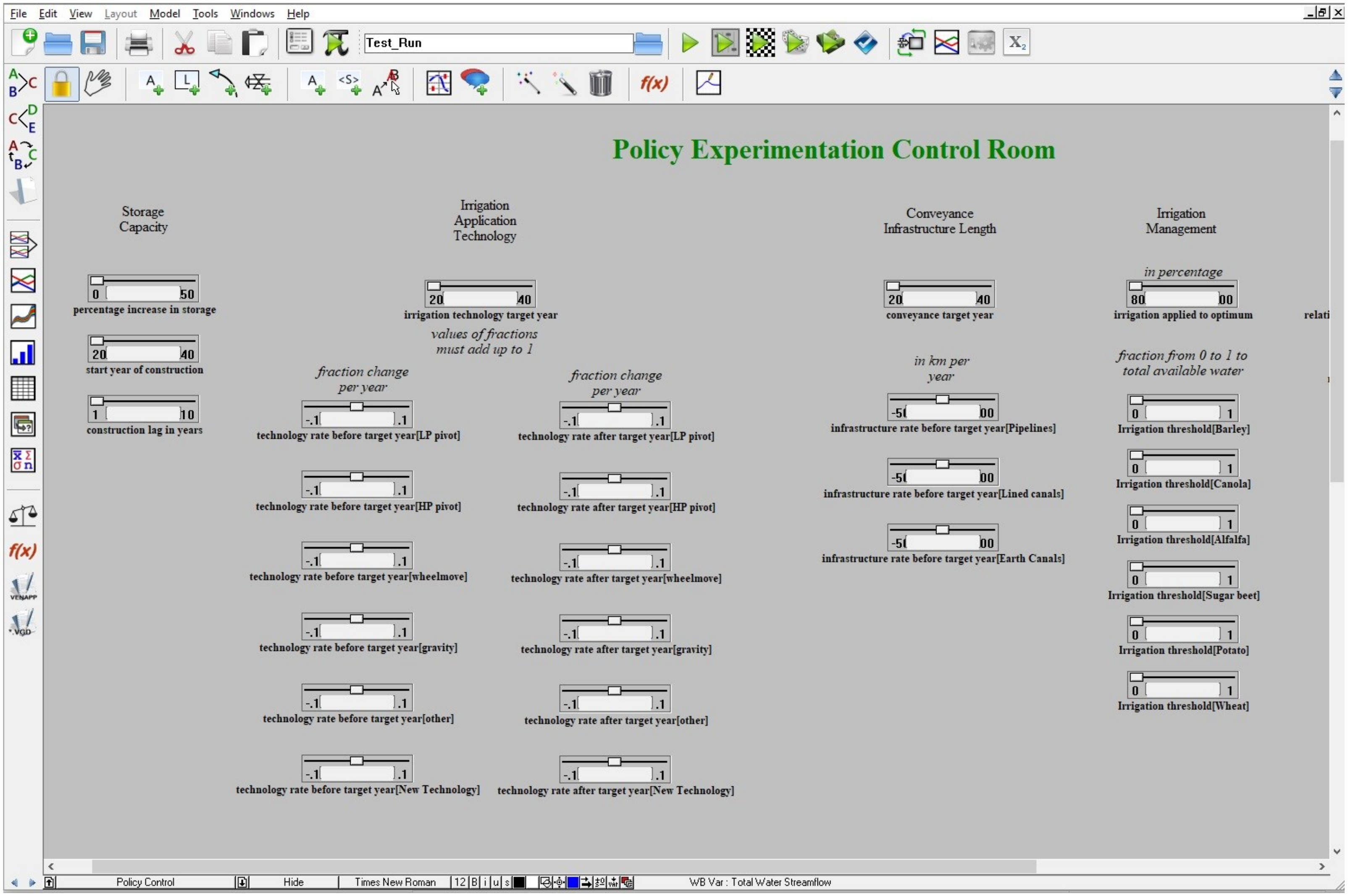


Figure A32. Policy experimentation control room view in AISS

A6 Model Equations

This section lists the equations for all the model variables including constants, lookup functions, subscripts, levels, and auxiliary variables. The list is arranged by alphabetic order for the ease of finding the variable of interest.

Model Constants

1. `Base temperature[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i32')`
2. `bface = 0.001165`
3. `bsted = 0.000138`
4. `building repairs[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c12')`
5. `Canopy expansion lower depletion threshold[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i73')`
6. `canopy expansion shape factor[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i74')`
7. `Canopy expansion upper depletion threshold[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i72')`
8. `canopy senescence stress shape factor[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i80')`
9. `Canopy senescence upper threshold depletion[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i78')`
10. `Canopy threshold lower threshold depletion[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i79')`
11. `CCx[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i40')`
12. `CDC[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i41')`
13. `CGC[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i39')`
14. `chemicals[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c7')`
15. `coeff a[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i94')`
16. `coeff b[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i95')`
17. `coeff c[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i96')`
18. `construction lag in years = 5`
19. `conveyance infrastructure length capacity = 7593`

20. Conveyance system method efficiency[Conveyance] = GET XLS CONSTANTS('data.xlsm', 'constants', 'I4*')
21. conveyance target year = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E31')
22. Correction factor = 1
23. crop insurance[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c8')
24. crop mix change rate[Fields] = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'I10*')
25. crop type[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i21')
26. cubic meter per ha to mm = 0.1
27. Curve Number CN[Fields] = 61
28. custom works and spec labor = GET XLS CONSTANTS('data.xlsm', 'economics', 'c13')
29. days to week = 7
30. decline factor fk = 1
31. deficit irrigation application = 1
32. degreeC to degree day = 1
33. district adjuster = 0
34. electricity percentage = 0.7
35. electricity rate = 0.04
36. Emergence or Recovery GDD[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i12')
37. Equation selector = 4
38. ERD shape factor[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i49')
39. expansion rate = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E4')
40. expontent coefficient a[Fields] = 1
41. factor = 8
42. fage[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i55')
43. fertilizers[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c6')
44. field capacity water content ratio[soil layers,Fields] = GET XLS CONSTANTS('data.xlsm', 'soildata', 'aa52')
45. FINAL TIME = 2505
46. Flag for irrigated and dry lands[Fields] = 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0
47. fsink = 0.4

48. fuel oil and lube[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c10')
49. gm per sqm to t per ha = 100
50. HI Factor[Fields] = 0.25
51. HIGC[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i63')
52. HIini[Fields] = 0.01
53. HIo[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i61')
54. Increase in harvest index per decade[Fields] = 0.015
55. infrastructure rate before target year[Conveyance] = GET XLS CONSTANTS('scenarios.xlsx', 'Scenarios', 'E32*')
56. Initial live water storage constant = GET XLS CONSTANTS('data.xlsm', 'constants', 'E4')
57. Initial plant coverage[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i37')
58. initial productivity ratio = 2
59. initial storage adjuster = 1
60. INITIAL TIME = 680
61. Instream flow needs IFN = 0.1
62. Irrigate switch = 1
63. Irrigation application method efficiency[Irrigation Method] = GET XLS CONSTANTS('data.xlsm', 'constants', 'L4*')
64. irrigation area year limit = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E5')
65. irrigation depletion recharge switch = 0
66. irrigation depletion to optimum = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E52')
67. irrigation districts owned storage = GET XLS CONSTANTS('data.xlsm', 'constants', 'd4')
68. irrigation technology target year = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E20')
69. Irrigation threshold[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i20')
70. Kex = 1.1
71. Ksat[soil layers,Fields] = GET XLS CONSTANTS('data.xlsm', 'soildata', 'ay52')
72. labor[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c14')
73. lag of improved irrigation scheduling = 0

74. length building up harvest index[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i18')
75. Linear of convex for canopy development = 1
76. Linear or convex for stomatal closure = 1
77. machinary repairs[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c11')
78. Maturity GDD end of yield[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i15')
79. Maximum canopy GDD[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i13')
80. Maximum crop transpiration coefficient Kctrx[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i54')
81. Maximum effective rooting depth Zx[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i47')
82. Maximum nitrogen[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i93')
83. Maximum root depth GDD[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i22')
84. Minimum effective rooting depth Zn[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i46')
85. Minimum GDD upper threshold[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i68')
86. Minimum growing degrees for full biomass production = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i61')
87. mm to cubic meter per hectare = 10
88. mm to m = 1000
89. modifier for initial conditions = 1
90. moisture ratio for crops[Fields] = 1, 0.2, 1, 1, 0.25, 1, 1, 0.2, 1, 1, 0.25, 1
91. motor efficiency = 0.92
92. natural gas percentage = 0.3
93. natural gas rate = 2
94. Nitrogen applied[Fields] = 224.2
95. Number of plants per hectare[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i38')
96. one week = 1
97. operating interest = GET XLS CONSTANTS('data.xlsm', 'economics', 'c16')

98. per acre to per hectare = 2.47105
99. percentage increase in storage = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E48')
100. permenant wilting point water content ratio[soil layers,Fields] = GET XLS CONSTANTS('data.xlsm', 'soildata', 'am52')
101. pivot size = 130
102. priority[Fields] = GET XLS CONSTANTS('data.xlsm', 'Control Sheet', 'k17*')
103. priority width = 2
104. provincial adjuster = 1
105. provincially owned storage = GET XLS CONSTANTS('data.xlsm', 'constants', 'c4')
106. pump efficiency = 0.8
107. pump operating pressure[LP pivot] = 30
108. pump operating pressure[HP pivot] = 60
109. pump operating pressure[wheelmove] = 50
110. pump operating pressure[gravity] = 0
111. pump operating pressure[Other] = 0
112. pump operating pressure[New Technology] = 20
113. Redistribution rate[l1,Fields] = 0
114. Redistribution rate[l2,Fields] = Drainage rate[l1,Fields]
115. Redistribution rate[l3,Fields] = Drainage rate[l2,Fields]
116. Redistribution rate[l4,Fields] = Drainage rate[l3,Fields]
117. Redistribution rate[l5,Fields] = Drainage rate[l4,Fields]
118. Redistribution rate[l6,Fields] = Drainage rate[l5,Fields]
119. Redistribution rate[l7,Fields] = Drainage rate[l6,Fields]
120. Redistribution rate[l8,Fields] = Drainage rate[l7,Fields]
121. Redistribution rate[l9,Fields] = Drainage rate[l8,Fields]
122. Redistribution rate[l10,Fields] = Drainage rate[l9,Fields]
123. Redistribution rate[l11,Fields] = Drainage rate[l10,Fields]
124. Redistribution rate[l12,Fields] = Drainage rate[l11,Fields]
125. Redistribution rate[l13,Fields] = Drainage rate[l12,Fields]
126. Redistribution rate[l14,Fields] = Drainage rate[l13,Fields]
127. Redistribution rate[l15,Fields] = Drainage rate[l14,Fields]
128. Reference CO2 = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i102')
129. reference demand value = 1.11771e+009

130. relative access to incentives factor = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E60')
131. relative number of extension visits = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E56')
132. Root zone layers activation flag[Fields,soil layers] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i107*')
133. saturation water content[soil layers,Fields] = GET XLS CONSTANTS('data.xlsm', 'soildata', 'o52')
134. SAVEPER = 0.125
135. scenescence trigger multiplier = 0.5
136. seed[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c5')
137. Senescence GDD[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i14')
138. simulation start year = 2017
139. Sowing depth Zini[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i48')
140. Start of yield and building up HI GDD[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i16')
141. start year of construction = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E47')
142. Stomatal closure lower threshold depletion[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i76')
143. Stomatal closure upper threshold depletion[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i75')
144. stomatal control shape factor[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i77')
145. storage[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c17')
146. system capacity flow rate = 7.6
147. Target efficiency by target year = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'F28')
148. technology rate after target year[Irrigation Method] = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'F21*')
149. technology rate before target year[Irrigation Method] = GET XLS CONSTANTS('scenarios.xlsx', 'scenarios', 'E21*')
150. Temperature adjustment lever = 0
151. Temperature stress effect on biomass switch = 0
152. thickness of soil layers[Fields,soil layers] = 100

153. TIME STEP = 0.125

154. ton to kg = 1000

155. trucking and marketing[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c9')

156. unit mm km to cubic meter = 1000

157. Upper temperature[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i33')

158. utilities[Fields] = GET XLS CONSTANTS('data.xlsm', 'economics', 'c15')

159. Water Conservation Objectives = 0.6

160. Water licence allocation = 3.45135e+009

161. Water Productivity WP[Fields] = GET XLS CONSTANTS('data.xlsm', 'cropdata', 'i60')

162. Water supply major feedback ON OFF = 1

163. weight of access to incentives = 0.25

164. weight of aridity index = 0.25

165. weight of extension services = 0.25

166. weight of relative productivity = 0.25

167. weight of water demand risk = 0.25

168. Zsurf[Fields] = 40

Model Lookups

169. access to incentive and subsidies LOOKUP (GET XLS LOOKUPS('data.xlsm', 'IrrigTechFn', 'R', 'S4'))

170. aridity index LOOKUP (GET XLS LOOKUPS('data.xlsm', 'IrrigTechFn', 'Ae', 'Ag4'))

171. CO2 lookup (GET XLS LOOKUPS('scenarios.xlsx', 'Scenarios', 'D', 'E39'))

172. Crop price LOOKUP[Fields] (GET XLS LOOKUPS('data.xlsm', 'cropprice', 'A', 'B2'))

173. ET04 lookup (GET XLS LOOKUPS('climate.xlsx', 'climate', 'e', 'k13'))

174. extension service LOOKUP (GET XLS LOOKUPS('data.xlsm', 'IrrigTechFn', 'N', 'o4'))

175. historic conveyance LOOKUP[Conveyance] (GET XLS LOOKUPS('scenarios.xlsx', 'historic', 'Z', 'AA4'))

176. historic crop mix LOOKUP[Fields] (GET XLS LOOKUPS('scenarios.xlsx', 'Historic', 'L', 'M4'))

177. historic irrigation area LOOKUP (GET XLS LOOKUPS('scenarios.xlsx', 'Historic', 'A', 'B4'))
178. historic irrigation technology LOOKUP[Irrigation Method] (GET XLS LOOKUPS('scenarios.xlsx', 'historic', 'D', 'E4'))
179. productivity LOOKUP (GET XLS LOOKUPS('data.xlsm', 'IrrigTechFn', 'aa', 'ab4'))
180. simulation year LOOKUP (GET XLS LOOKUPS('data.xlsm', 'Timer', 'L', 'M14'))
181. start season flag LOOKUP (GET XLS LOOKUPS('data.xlsm', 'Timer', 'T', 'U14'))
182. stock drain LOOKUP (GET XLS LOOKUPS('data.xlsm', 'timer', 'p', 'q14'))
183. storage flag LOOKUP (GET XLS LOOKUPS('data.xlsm', 'Timer', 'W', 'X14'))
184. streamflow LOOKUP (GET XLS LOOKUPS('streamflow.xlsx', 'Streamflow', 'A', 'B2'))
185. Tmax lookup (GET XLS LOOKUPS('climate.xlsx', 'climate', 'e', 'g13'))
186. Tmin lookup (GET XLS LOOKUPS('climate.xlsx', 'climate', 'e', 'h13'))
187. water supply reliability LOOKUP (GET XLS LOOKUPS('data.xlsm', 'IrrigTechFn', 'v', 'x4'))
188. Weekly Rainfall LOOKUP (GET XLS LOOKUPS('climate.xlsx', 'climate', 'e', 'f13'))

Model Subscripts

189. Conveyance : Pipelines,Lined canals,Earth Canals
190. Fields : GET XLS SUBSCRIPT ,'', 't9', 'i9', 'cropdata', 'data.xlsm', 'data.xlsm', 'cropdata', 'i9', 't9', ''
191. Irrigation Method : LP pivot,HP pivot,wheelmove,gravity,Other,New Technology
192. soil layers : l1,l2,l3,l4,l5,l6,l7,l8,l9,l10,l11,l12,l13,l14,l15

Model Levels

193. Aboveground Biomass[Fields] = INTEG(Biomass accumulation rate[Fields] - Drain Biomass Stock[Fields] , 0)
194. Canopy Cover Stock[Fields] = SINTEG(Canopy in exp growth rate[Fields] + Canopy in exp decay rate[Fields] - Canopy level[Fields] - 0 * Canopy

decay rate[Fields] - canopy out adjusted[Fields] - drain canopy stock[Fields] , 0, 0, 1, :NA:, :NA:, :NA:)

195. CGDD from emergence or recovering[Fields] = INTEG(GDD Rate from emergence[Fields] - Drain stock 1[Fields] , 0)
196. CGDD from flowering[Fields] = INTEG(GDD Rate from flowering[Fields] - Drain stock 3[Fields] , 0)
197. CGDD from senescence[Fields] = INTEG(GDD Rate from Senescence[Fields] - Drain stock 2[Fields] , 0)
198. CGDD from sowing or transplanting[Fields] = INTEG(GDD Rate from planting[Fields] - Drain stock 5[Fields] , 0)
199. Conveyance infrastructure length[Conveyance] = SINTEG(Infrastructure expansion[Conveyance] - Infrastructure retirement[Conveyance] , historic conveyance[Conveyance] , 0, 7593, :NA:, :NA:, :NA:)
200. Crop mix[Fields] = INTEG(Crops adding rate[Fields] - Crops retiring rate[Fields] , historic crop mix[Fields])
201. Crop residue in soil[Fields] = INTEG(Residue accumulation[Fields] - clear residue[Fields] , 0)
202. Cumulative Actual Evaporation[Fields] = INTEG(actual evaporation rate[Fields] - drain actual evaporation[Fields] , 0)
203. Cumulative Actual Evapotranspiration[Fields] = INTEG(actual evapotranpiration rate[Fields] , 0)
204. Cumulative Actual Transpiration[Fields] = INTEG(actual transpiration rate[Fields] , 0)
205. Cumulative growing degree days[Fields] = INTEG(GDD Inflow[Fields] - Drain CGDD stock 2[Fields] , 0)
206. Cumulative Potential Evaporation[Fields] = INTEG(potential evaporation rate[Fields] - drain cpe[Fields] , 0)
207. Cumulative precipitation = INTEG(weekly rain - drain rain , 0)
208. Cumulative Ref ET = INTEG(ref et in - ref et out , 0)
209. Cumulative Reference Evapotranspiration = INTEG(Weekly evapotranspiration rate , 0)
210. Deep percolated precipitation[Fields] = INTEG(deep percolation rate[Fields] - drain deep percolated precipitation stock[Fields] , 0)
211. Deep percolation[Fields] = INTEG(Drainage rate[l15,Fields] , 0)
212. Deficit counter = INTEG(deficit counter rate - deficit drain , 0)
213. delay fixed canopy decay max[Fields] = DELAY FIXED (canopy decay max[Fields] ,TIME STEP , 0)

214. delayed CGDD[Fields] = DELAY FIXED (Cumulative growing degree days[Fields] ,TIME STEP , 0)
215. delayed conveyance[Conveyance] = DELAY FIXED (historic conveyance[Conveyance] ,1, historic conveyance[Conveyance])
216. delayed historic crop mix[Fields] = DELAY FIXED (historic crop mix[Fields] ,1, historic crop mix[Fields])
217. delayed historic irrigation area = DELAY FIXED (Historic irrigation Area ,1, Historic irrigation Area)
218. delayed irrigation flag[Fields] = DELAY FIXED (Irrigation flag[Fields] ,0, 0)
219. delayed net irrigation requirements[Fields] = DELAY FIXED (Net Irrigation Requirement[Fields] ,TIME STEP , 0)
220. delayed technology[Irrigation Method] = DELAY FIXED (historic irrigation technology[Irrigation Method] ,1, historic irrigation technology[Irrigation Method])
221. Effective Rooting Depth[Fields] = INTEG(Root growth[Fields] - drain ERD stock[Fields] , Minimum effective rooting depth Zn[Fields])
222. Harvest Index stock[Fields] = INTEG(Harvest Index Rate[Fields] - drain HI stock[Fields] - Harvest index out[Fields] , HIini[Fields])
223. Irrigation application technology[Irrigation Method] = SINTEG(Irrigation technology adoption rate[Irrigation Method] - Irrigation technology retirement rate[Irrigation Method] , historic irrigation technology[Irrigation Method] , 0, 1, :NA:, :NA:, :NA:)
224. Irrigation Area = INTEG(Area Expansion , Historic irrigation Area)
225. irrigation water available[Fields] = INTEG(rate 1[Fields] - rate 1 drain[Fields] , 0)
226. irrigation water required[Fields] = INTEG(rate 2[Fields] - rate 2 drain[Fields] , 0)
227. Irrigation water to be applied[Fields] = DELAY FIXED (Water available to apply per irrigation event[Fields] * percentage applied of required / 100,delay for irrigation , Water available to apply per irrigation event[Fields])
228. Live Water Storage = INTEG(Diversion to Storage + Precipitation - Demand Withdrawal - Evaporation - Spill off , initial live storage input parameter)
229. Net Irrigation Water Applied[Fields] = INTEG(Irrigation rate[Fields] - drain net irrigation water applied stock[Fields] , 0)

230. Net Irrigation Water Demand[Fields] = INTEG(Net irrigation demand inflow[Fields] - drain net irrigation water demand stock[Fields] , 0)
231. Precipitation used by fields[Fields] = INTEG(effective precipitation rate[Fields] - drain precipitation stoc[Fields] , 0)
232. senescence trigger accumulator[Fields] = INTEG(rate of accumulation[Fields] - Drain stock[Fields] , 0)
233. soil layers water content[soil layers,Fields] = SINTEG(Irrigation per soil layer[soil layers,Fields] + Precipitation rate[Fields,soil layers] + Redistribution rate[soil layers,Fields] - Drainage rate[soil layers,Fields] - Evaporation rate from top layer[soil layers,Fields] - Transpiration rate[soil layers,Fields] + Re initialization[soil layers,Fields] , Initial soil water content[soil layers,Fields] , 0, :NA:, :NA:, :NA:, :NA:)
234. Spill off water = INTEG(Spill off , 0)
235. start of season stock[Fields] = INTEG(season in[Fields] - season out[Fields] , 0)
236. Time Stock for aging and senescence[Fields] = INTEG(Time rate 2[Fields] - Drain time stock 2[Fields] , 0)
237. Total Water Streamflow = INTEG(Streamflow rate - drain streamflow supply stock , 0)
238. Total Water Supply = INTEG(total water supply rate - drain water supply stock , 0)
239. Total Water Withdrawal = INTEG(Demand Withdrawal - drain total demand stock , 0)

Model Auxiliary Variables

240. access to incentives score = access to incentive and subsidies LOOKUP (relative access to incentives factor)
241. Actual CO2 = CO2 lookup (simulation year)
242. Actual evaporation[Fields] = SUM (Evaporation rate from top layer[soil layers!,Fields])
243. actual evaporation rate[Fields] = Actual evaporation[Fields]
244. actual evapotranpiration rate[Fields] = Actual transpiration[Fields] + Actual evaporation[Fields]
245. Actual transpiration[Fields] = SUM (Transpiration rate[soil layers!,Fields])

246. actual transpiration rate[Fields] = Actual transpiration[Fields]
247. Adjusted Canopy Cover[Fields] = Canopy cover flag[Fields] * (1.72 * Canopy Cover[Fields] - Canopy Cover[Fields] ^ 2 + 0.3 * Canopy Cover[Fields] ^ 3)
248. Adjusted CDC[Fields] = IF THEN ELSE (Canopy senescence water stress coefficient Kssen[Fields] >= 0.99, CDC[Fields] , (1 - Canopy senescence water stress coefficient Kssen[Fields] ^ (factor)) * CDC[Fields]) * 0 + CDC[Fields]
249. Adjusted CGC[Fields] = CGC[Fields] * Canopy development water stress coefficient Ksexp[Fields]
250. Adjusted depletion for canopy expansion[Fields] = IF THEN ELSE (Root zone depletion[Fields] < Canopy expansion upper depletion threshold[Fields] * Root zone TAW[Fields] , 0, IF THEN ELSE (Root zone depletion[Fields] > Canopy expansion lower depletion threshold[Fields] * Root zone TAW[Fields] , 1, Root zone depletion[Fields] - Canopy expansion upper depletion threshold[Fields] * Root zone TAW[Fields]))
251. Adjusted depletion for canopy senescence[Fields] = IF THEN ELSE (Root zone depletion[Fields] <= Canopy senescence upper threshold depletion[Fields] * Root zone TAW[Fields] , 0, IF THEN ELSE (Root zone depletion[Fields] > Canopy threshold lower threshold depletion[Fields] * Root zone TAW[Fields] , 1, Root zone depletion[Fields] - Canopy senescence upper threshold depletion[Fields] * Root zone TAW[Fields]))
252. Adjusted depletion for stomatal closure[Fields] = IF THEN ELSE (Root zone depletion[Fields] <= Stomatal closure upper threshold depletion[Fields] * Root zone TAW[Fields] , 0, IF THEN ELSE (Root zone depletion[Fields] > Stomatal closure lower threshold depletion[Fields] * Root zone TAW[Fields] , 1, Root zone depletion[Fields] - Stomatal closure upper threshold depletion[Fields] * Root zone TAW[Fields]))
253. Adjusted Kctrx[Fields] = MAX (0, (Maximum crop transpiration coefficient Kctrx[Fields] - fage[Fields] / 100 * CCx[Fields] * Time Stock for aging and senescence[Fields]) * fsen[Fields])
254. Air dry soil water content ratio[soil layers,Fields] = 1 / 2 * permenant wilting point water content ratio[soil layers,Fields]
255. annual deficit flag = IF THEN ELSE (deficit delayed > 0, 1, 0) * Water supply major feedback ON OFF
256. Area Expansion = IF THEN ELSE (simulation year < simulation start year , historic area rate , IF THEN ELSE (simulation year <= irrigation area

year limit + 1, expansion rate * per year to per week * Decision score to expand irrigation area , 0)) * IF THEN ELSE (annual deficit flag = 0, 1, 0)

257. Area of resevoirs = 79.34 * 10
258. Aridity Index = SAMPLE IF TRUE(drain , ZIDZ (Cumulative precipitation , Cumulative Ref ET) , 0.3)
259. aridity index score = aridity index LOOKUP (Aridity Index)
260. Average pumping KWh[Fields] = SUM (water horsepower required[Irrigation Method!]) * pumping hours required per pivot[Fields] / motor efficiency
261. Average temperature[Fields] = (Tmax adjusted[Fields] + Tmin adjusted[Fields]) / 2
262. Biomass accumulation rate[Fields] = one week * Water Productivity Adjusted[Fields] * ZIDZ (Actual transpiration[Fields] , Weekly Reference Evapotranspiration) * 7 * Biomass formation flag[Fields] * Temperature biomass stress Ks[Fields]
263. Biomass formation flag[Fields] = IF THEN ELSE (CGDD from sowing or transplanting[Fields] >= Emergence or Recovery GDD[Fields] , 1, 0)
264. BM[Fields] = SAMPLE IF TRUE(drain , Aboveground Biomass[Fields] , 0)
265. Canopy Cover[Fields] = IF THEN ELSE (Canopy cover flag[Fields] , MIN (MAX (0, Canopy Cover Stock[Fields] + CC0[Fields]) , 0.98 * CCx[Fields]) , 0)
266. Canopy cover flag[Fields] = CGDD flag[Fields]
267. canopy decay max[Fields] = IF THEN ELSE (Canopy decay rate[Fields] :AND: Canopy decay rate[Fields] > delay fixed canopy decay max[Fields] , Canopy decay rate[Fields] , 0)
268. Canopy decay rate[Fields] = IF THEN ELSE (Canopy Cover[Fields] <= 0.01, 0, IF THEN ELSE (scenescence trigger[Fields] :AND: Canopy cover flag[Fields] , conversion coefficient[Fields] * 0.05 * Adjusted CDC[Fields] * EXP (Adjusted CDC[Fields] / CCx[Fields] * CGDD from senescence[Fields]) , 0))
269. Canopy development water stress coefficient Ksexp[Fields] = IF THEN ELSE (Root zone relative depletion[Fields] < Canopy expansion upper depletion threshold[Fields] , 1, IF THEN ELSE (Root zone relative depletion[Fields] > Canopy expansion lower depletion threshold[Fields] , 0, Linear of convex for canopy development * (1 - ((EXP (Relative depletion between upper and lower thresholds for canopy expansion[Fields] * canopy expansion shape factor[Fields]) - 1) / (EXP (canopy expansion

shape factor[Fields]) - 1))) + (1 - Relative depletion between upper and lower thresholds for canopy expansion[Fields]) * (1 - Linear of convex for canopy development)))

270. Canopy in exp decay rate[Fields] = Canopy cover flag[Fields] * IF THEN ELSE (Canopy in exp growth rate[Fields] , 0, IF THEN ELSE (Canopy Cover[Fields] <= 0.98 * CCx[Fields] , CGC[Fields] * conversion coefficient[Fields] * 0.25 * CCx[Fields] ^ 4 / CC0[Fields] * EXP (- Correction factor * (CGDD from emergence or recovering[Fields]) * CGC[Fields]) , 0))
271. Canopy in exp growth rate[Fields] = MAX (0, Canopy cover flag[Fields] * IF THEN ELSE (Canopy Cover Stock[Fields] < 0.5 * CCx[Fields] :AND: (CC0[Fields] * EXP (CGC[Fields] * CGDD from emergence or recovering[Fields]) * conversion coefficient[Fields] * Adjusted CGC[Fields] * TIME STEP + Canopy Cover Stock[Fields]) < 0.5 * CCx[Fields] , CC0[Fields] * EXP (CGC[Fields] * CGDD from emergence or recovering[Fields]) * conversion coefficient[Fields] * Adjusted CGC[Fields] , IF THEN ELSE (Canopy Cover Stock[Fields] >= 0.5 * CCx[Fields] :AND: Canopy Cover Stock[Fields] <= CCx[Fields] , 0, 0)))
272. Canopy level[Fields] = IF THEN ELSE (Canopy Cover Stock[Fields] >= CCx[Fields] , (Canopy Cover Stock[Fields] - CCx[Fields]) / TIME STEP , 0)
273. canopy out adjusted[Fields] = IF THEN ELSE (Canopy decay rate[Fields] , canopy decay max[Fields] , 0)
274. Canopy senescence water stress coefficient Kssen[Fields] = IF THEN ELSE (Root zone relative depletion[Fields] <= Canopy senescence upper threshold depletion[Fields] , 1, IF THEN ELSE (Root zone relative depletion[Fields] > Canopy threshold lower threshold depletion[Fields] , 0, 1 - ((EXP (canopy senescence stress shape factor[Fields] * Relative depletion between upper and lower thresholds for canopy senescence[Fields]) - 1) / (EXP (canopy senescence stress shape factor[Fields]) - 1))))
275. CC0[Fields] = Initial plant coverage[Fields] * Number of plants per hectare[Fields] / 1e+008
276. CGDD flag[Fields] = IF THEN ELSE (CGDD from sowing or transplanting[Fields] >= Emergence or Recovery GDD[Fields] , 1, 0)
277. clear residue[Fields] = IF THEN ELSE (MODULO (Time , 52) = 0, Crop residue in soil[Fields] / TIME STEP , 0)

278. Contribution margin[Fields] = MAX (0, Crop revenue per hectare[Fields] - Expenses[Fields])
279. conversion coefficient[Fields] = MAX (0, (Cumulative growing degree days[Fields] - delayed CGDD[Fields]) / TIME STEP)
280. Conveyance system efficiency = SUM (Conveyance system method efficiency[Conveyance!] * Conveyance infrastructure length[Conveyance!]) / conveyance infrastructure length capacity
281. Crop revenue per hectare[Fields] = Crop selling price per ton[Fields] * Dry matter crop yield[Fields] * Flag for irrigated and dry lands[Fields] / moisture ratio for crops[Fields]
282. Crop selling price per ton[Fields] = Crop price LOOKUP[Fields] (simulation year)
283. Crop transpiration coefficient Kctr[Fields] = Adjusted Kctrx[Fields] * Adjusted Canopy Cover[Fields]
284. Crops adding rate[Fields] = MAX (0, IF THEN ELSE (simulation year >= simulation start year , crop mix change rate[Fields] * per year to per week , historic crop mix rate[Fields]))
285. Crops retiring rate[Fields] = MIN (0, IF THEN ELSE (simulation year >= simulation start year , crop mix change rate[Fields] * per year to per week , historic crop mix rate[Fields])) * -1
286. CY[Fields] = SAMPLE IF TRUE(drain , Dry matter crop yield[Fields] , 0)
287. Decision score to adopt improved irrigation technologies = IF THEN ELSE (simulation year < simulation start year , 1, (access to incentives score * weight of access to incentives + extension services score * weight of extension services + productivity score * weight of relative productivity + water demand risk score * weight of water demand risk))
288. Decision score to expand irrigation area = IF THEN ELSE (simulation year < simulation start year , 1, aridity index score * weight of aridity index * 2 + water demand risk score * weight of water demand risk * 2 + 0 * weight of relative productivity * productivity score)
289. deep percolation rate[Fields] = season flag[Fields] * Drainage rate[l15,Fields]
290. deficit counter rate = deficit flag
291. deficit delayed = SAMPLE IF TRUE(drain , Deficit counter , Deficit counter)
292. deficit drain = drain * Deficit counter / TIME STEP
293. deficit flag = IF THEN ELSE (water potential deficit < 0, 1, 0)

294. delay for irrigation = lag of improved irrigation scheduling * 8 / 7
295. Delta = 2504 * EXP ((17.27 * Tavg) / (Tavg + 237.3)) / (Tavg + 237.3) ^ 2
296. Demand Withdrawal = IF THEN ELSE ((SUM (Irrigation rate[Fields!] * total area of each field at the start of the season[Fields!] * mm to cubic meter per hectare) / (Irrigation application efficiency * Conveyance system efficiency)) * TIME STEP >= Live Water Storage , 0, SUM (Irrigation rate[Fields!] * total area of each field at the start of the season[Fields!] * mm to cubic meter per hectare) / (Irrigation application efficiency * Conveyance system efficiency))
297. Depletion to saturation[soil layers,Fields] = MAX (0, soil layers SAT[soil layers,Fields] - soil layers water content[soil layers,Fields])
298. Diversion to Storage = Streamflow rate * storage flag
299. drain = IF THEN ELSE (MODULO (stock drain LOOKUP (Time) , 1) = 0, 1, 0)
300. drain actual evaporation[Fields] = Cumulative Actual Evaporation[Fields] * drain / TIME STEP
301. Drain Biomass Stock[Fields] = drain * Aboveground Biomass[Fields] / TIME STEP
302. drain canopy stock[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , MAX (0, (Canopy Cover Stock[Fields]) / TIME STEP) , 0)
303. Drain CGDD stock 2[Fields] = drain * Cumulative growing degree days[Fields] / TIME STEP
304. drain cpe[Fields] = Cumulative Potential Evaporation[Fields] / TIME STEP * drain
305. drain deep percolated precipitation stock[Fields] = IF THEN ELSE (MODULO (Time , 52) = 0, Deep percolated precipitation[Fields] / TIME STEP , 0)
306. drain ERD stock[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , MAX (0, (Effective Rooting Depth[Fields] - Root growth[Fields] - Minimum effective rooting depth Zn[Fields]) / TIME STEP) , 0)
307. drain HI stock[Fields] = (Harvest Index stock[Fields] - HIini[Fields]) / TIME STEP * drain
308. drain net irrigation water applied stock[Fields] = drain * Net Irrigation Water Applied[Fields] / TIME STEP
309. drain net irrigation water demand stock[Fields] = drain * Net Irrigation Water Demand[Fields] / TIME STEP

310. drain precipitation stoc[Fields] = IF THEN ELSE (MODULO (Time , 52) = 0, Precipitation used by fields[Fields] / TIME STEP , 0)
311. drain rain = drain * Cumulative precipitation / TIME STEP
312. Drain stock[Fields] = drain * senescence trigger accumulator[Fields] / TIME STEP
313. Drain stock 1[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , CGDD from emergence or recovering[Fields] / TIME STEP + GDD Rate from emergence[Fields] , 0)
314. Drain stock 2[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , CGDD from senescence[Fields] / TIME STEP + GDD Rate from Senescence[Fields] , 0)
315. Drain stock 3[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , CGDD from flowering[Fields] / TIME STEP + GDD Rate from flowering[Fields] , 0)
316. Drain stock 5[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , GDD Rate from planting[Fields] + CGDD from sowing or transplanting[Fields] / TIME STEP , 0)
317. drain streamflow supply stock = drain * Total Water Streamflow / TIME STEP
318. Drain time stock 2[Fields] = IF THEN ELSE (end of season stock drainage flag[Fields] , Time Stock for aging and senescence[Fields] / TIME STEP , 0)
319. drain total demand stock = drain * Total Water Withdrawal / TIME STEP
320. drain water supply stock = drain * Total Water Supply / TIME STEP
321. Drainage by layer using Aquacrop approach[soil layers,Fields] = drainage function[soil layers,Fields] * thickness of soil layers[Fields,soil layers]
322. drainage characteristic tau[soil layers,Fields] = 0.0866 * Ksat[soil layers,Fields] ^ 0.35
323. drainage function[soil layers,Fields] = IF THEN ELSE (soil layers water content ratio[soil layers,Fields] <= field capacity water content ratio[soil layers,Fields] , 0, MAX (0, MIN ((saturation water content[soil layers,Fields] - field capacity water content ratio[soil layers,Fields]) * drainage characteristic tau[soil layers,Fields] , drainage characteristic tau[soil layers,Fields] * (soil layers water content ratio[soil layers,Fields] - field capacity water content ratio[soil layers,Fields]) * ((EXP (soil layers water content

ratio[soil layers,Fields] - field capacity water content ratio[soil layers,Fields]) - 1) / (EXP (saturation water content[soil layers,Fields] - field capacity water content ratio[soil layers,Fields]) - 1)))))

324. Drainage rate[soil layers,Fields] = Drainge[soil layers,Fields] / TIME STEP

325. Drainge[l1,Fields] = MIN (excess drainage water[l1,Fields] * one week , layer capacity for drainage storage[l2,Fields] * one week)

326. Drainge[l2,Fields] = MIN (excess drainage water[l2,Fields] * one week , layer capacity for drainage storage[l3,Fields] * one week)

327. Drainge[l3,Fields] = MIN (excess drainage water[l3,Fields] * one week , layer capacity for drainage storage[l4,Fields] * one week)

328. Drainge[l4,Fields] = MIN (excess drainage water[l4,Fields] * one week , layer capacity for drainage storage[l5,Fields] * one week)

329. Drainge[l5,Fields] = MIN (excess drainage water[l5,Fields] * one week , layer capacity for drainage storage[l6,Fields] * one week)

330. Drainge[l6,Fields] = MIN (excess drainage water[l6,Fields] * one week , layer capacity for drainage storage[l7,Fields] * one week)

331. Drainge[l7,Fields] = MIN (excess drainage water[l7,Fields] * one week , layer capacity for drainage storage[l8,Fields] * one week)

332. Drainge[l8,Fields] = MIN (excess drainage water[l8,Fields] * one week , layer capacity for drainage storage[l9,Fields] * one week)

333. Drainge[l9,Fields] = MIN (excess drainage water[l9,Fields] * one week , layer capacity for drainage storage[l10,Fields] * one week)

334. Drainge[l10,Fields] = MIN (excess drainage water[l10,Fields] * one week , layer capacity for drainage storage[l11,Fields] * one week)

335. Drainge[l11,Fields] = MIN (excess drainage water[l11,Fields] * one week , layer capacity for drainage storage[l12,Fields] * one week)

336. Drainge[l12,Fields] = MIN (excess drainage water[l12,Fields] * one week , layer capacity for drainage storage[l13,Fields] * one week)

337. Drainge[l13,Fields] = MIN (excess drainage water[l13,Fields] * one week , layer capacity for drainage storage[l14,Fields] * one week)

338. Drainge[l14,Fields] = MIN (excess drainage water[l14,Fields] * one week , layer capacity for drainage storage[l15,Fields] * one week)

339. Drainge[l15,Fields] = excess drainage water[l15,Fields] * one week

340. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l1] = MIN (Drainage by layer using Aquacrop approach[l1,Fields] , layer capacity for drainage storage[l2,Fields])
341. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l2] = MIN (Drainage by layer using Aquacrop approach[l2,Fields] , layer capacity for drainage storage[l3,Fields])
342. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l3] = MIN (Drainage by layer using Aquacrop approach[l3,Fields] , layer capacity for drainage storage[l4,Fields])
343. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l4] = MIN (Drainage by layer using Aquacrop approach[l4,Fields] , layer capacity for drainage storage[l5,Fields])
344. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l5] = MIN (Drainage by layer using Aquacrop approach[l5,Fields] , layer capacity for drainage storage[l6,Fields])
345. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l6] = MIN (Drainage by layer using Aquacrop approach[l6,Fields] , layer capacity for drainage storage[l7,Fields])
346. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l7] = MIN (Drainage by layer using Aquacrop approach[l7,Fields] , layer capacity for drainage storage[l8,Fields])
347. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l8] = MIN (Drainage by layer using Aquacrop approach[l8,Fields] , layer capacity for drainage storage[l9,Fields])
348. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l9] = MIN (Drainage by layer using Aquacrop approach[l9,Fields] , layer capacity for drainage storage[l10,Fields])
349. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l10] = MIN (Drainage by layer using Aquacrop approach[l10,Fields] , layer capacity for drainage storage[l11,Fields])
350. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l11] = MIN (Drainage by layer using Aquacrop approach[l11,Fields] , layer capacity for drainage storage[l12,Fields])
351. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l12] = MIN (Drainage by layer using Aquacrop approach[l12,Fields] , layer capacity for drainage storage[l13,Fields])

352. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l13] = MIN (Drainage by layer using Aquacrop approach[l13,Fields] , layer capacity for drainage storage[l14,Fields])
353. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l14] = MIN (Drainage by layer using Aquacrop approach[l14,Fields] , layer capacity for drainage storage[l15,Fields])
354. Drainge by layer using AquaCrop approach with maximum allowable storage[Fields,l15] = Drainage by layer using Aquacrop approach[l15,Fields]
355. Dry matter crop yield[Fields] = Aboveground Biomass[Fields] * Harvest Index[Fields]
356. Dry matter crop yield with fertilizer[Fields] = IF THEN ELSE (Flag for irrigated and dry lands[Fields] = 1, Dry matter crop yield[Fields] * Relative yield response to nitrogen[Fields] , Dry matter crop yield[Fields])
357. ea = Relative humidity / 100 * es
358. Effective precipitation events[Fields] = Rainfall weekly event - Runoff[Fields]
359. effective precipitation rate[Fields] = season flag[Fields] * Infiltration precipitation[Fields]
360. Effective rooting depth adjusted[Fields] = MIN (Maximum effective rooting depth Zx[Fields] , Effective Rooting Depth[Fields])
361. end of season stock drainage flag[Fields] = IF THEN ELSE (Cumulative growing degree days[Fields] > Maturity GDD end of yield[Fields] , 1, 0)
362. es = 0.6108 * EXP ((17.27 * Tavg) / (Tavg + 237.3))
363. ET01 = 0.134 * Tdiff + 0.0109 * Tavg + 0.708 * Delta * Extraterrestrial rad Ra - 0.669
364. ET02 = 0.051 * Tdiff + 0.131 * Tavg + 0.846 * Delta * Extraterrestrial rad Ra - 3.18 * ea + 1.28
365. ET03 = 0.077 * Tdiff + 0.114 * Tavg + 0.832 * Delta * Extraterrestrial rad Ra - 2.77 * ea + 0.269 * Wind speed + 0.053
366. ET04 using lookup = LOOKUP BACKWARD (ET04 lookup , Time)
367. Evaporation = IF THEN ELSE (Area of resevoirs * Weekly Reference Evapotranspiration * unit mm km to cubic meter * TIME STEP >= Live Water Storage , 0, Area of resevoirs * Weekly Reference Evapotranspiration * unit mm km to cubic meter)

368. Evaporation rate[Fields] = Potential evaporation[Fields] * Evaporation reduction coefficient Kr[Fields]
369. Evaporation rate from top layer[l1,Fields] = IF THEN ELSE (soil layers water content[l1,Fields] - soil layers AD[l1,Fields] <= 0, 0, Evaporation rate[Fields])
370. Evaporation rate from top layer[l2,Fields] = IF THEN ELSE (soil layers water content[l2,Fields] - soil layers AD[l2,Fields] <= 0, 0, MAX (0, Evaporation rate[Fields] - Evaporation rate from top layer[l1,Fields]))
371. Evaporation rate from top layer[l3,Fields] = 0
372. Evaporation rate from top layer[l4,Fields] = 0
373. Evaporation rate from top layer[l5,Fields] = 0
374. Evaporation rate from top layer[l6,Fields] = 0
375. Evaporation rate from top layer[l7,Fields] = 0
376. Evaporation rate from top layer[l8,Fields] = 0
377. Evaporation rate from top layer[l9,Fields] = 0
378. Evaporation rate from top layer[l10,Fields] = 0
379. Evaporation rate from top layer[l11,Fields] = 0
380. Evaporation rate from top layer[l12,Fields] = 0
381. Evaporation rate from top layer[l13,Fields] = 0
382. Evaporation rate from top layer[l14,Fields] = 0
383. Evaporation rate from top layer[l15,Fields] = 0
384. Evaporation reduction coefficient Kr[Fields] = IF THEN ELSE (soil layers water content[l1,Fields] >= (soil layers FC[l1,Fields] - Readily evaporable water[Fields]) , 1, MAX (MIN ((EXP (decline factor fk * SWC rel[Fields]) - 1) / (EXP (decline factor fk) - 1) , 1) , 0))
385. excess drainage water[soil layers,Fields] = MAX (0, soil layers water content[soil layers,Fields] - soil layers FC[soil layers,Fields])
386. Expenses[Fields] = (non water variable costs[Fields] + Pumping cost[Fields]) * per acre to per hectare
387. extension services score = extension service LOOKUP (relative number of extension visits)
388. fco2 = (Actual CO2 / Reference CO2) / (1 + (Actual CO2 - Reference CO2) * ((1 - weighting factor) * bsted + weighting factor * (fsink * bsted + (1 - fsink) * bface)))
389. Field gross irrigation water applied at farm gate[Fields] = end of season stock drainage flag[Fields] * total area of each field at the start of

the season[Fields] * Net irrigation water applied per hectare of crop[Fields] / Irrigation application efficiency

390. Field gross irrigation water demand at farm gate[Fields] = total area of each field at the start of the season[Fields] * Field gross irrigation water demand per hectare at farm gate[Fields]
391. Field gross irrigation water demand per hectare at farm gate[Fields] = Net Irrigation Water Demand[Fields] * 10 / Irrigation application efficiency * deficit irrigation application
392. fsen[Fields] = IF THEN ELSE (scenescence trigger[Fields] , (Canopy Cover[Fields] / CCx[Fields]) ^ expontent coefficient a[Fields] , 1)
393. GDD Inflow[Fields] = Weekly Growing Degrees[Fields] * start of season flag[Fields]
394. GDD Rate from emergence[Fields] = CGDD flag[Fields] * Weekly Growing Degrees[Fields]
395. GDD Rate from flowering[Fields] = IF THEN ELSE (CGDD from sowing or transplanting[Fields] >= Start of yield and building up HI GDD[Fields] , Weekly Growing Degrees[Fields] , 0)
396. GDD Rate from planting[Fields] = Weekly Growing Degrees[Fields] * start of season flag[Fields]
397. GDD Rate from Senescence[Fields] = Weekly Growing Degrees[Fields] * IF THEN ELSE (scenescence trigger[Fields] , 1, 0)
398. gross irrigation water applied per field[Fields] = Net irrigation water applied per hectare of crop[Fields] * total area of each field at the start of the season[Fields] / Irrigation application efficiency
399. gross total irrigation water applied at headworks[Fields] = Irrigation water applied per hectare of crop at farm gate[Fields] / Conveyance system efficiency
400. Growing Degree Days[Fields] = Tavg adjusted[Fields] * degreeC to degree day - Base temperature[Fields] * degreeC to degree day
401. Harvest Index[Fields] = MIN (Harvest Index stock[Fields] , Ref HI[Fields])
402. Harvest index out[Fields] = IF THEN ELSE (Harvest Index stock[Fields] >= Ref HI[Fields] , Harvest Index Rate[Fields] + (Harvest Index stock[Fields] - Ref HI[Fields]) / TIME STEP , 0)
403. Harvest Index Rate[Fields] = IF THEN ELSE (Canopy Cover[Fields] <= 0.05, 0, 1) * IF THEN ELSE (CGDD from sowing or transplanting[Fields] >= Start of yield and building up HI GDD[Fields] , 1, 0) * IF THEN ELSE (CGDD

from flowering[Fields] , IF THEN ELSE (crop type[Fields] = 1 :AND: CGDD from flowering[Fields] <> 0, ((HIini[Fields] * Ref HI[Fields] * (Ref HI[Fields] - HIini[Fields]) * HIGC[Fields] * EXP (HIGC[Fields] * CGDD from flowering[Fields])) / (HIini[Fields] * (EXP (HIGC[Fields] * CGDD from flowering[Fields]) - 1) + Ref HI[Fields]) ^ 2) * conversion coefficient[Fields] , IF THEN ELSE (crop type[Fields] = 2, IF THEN ELSE (Harvest Index stock[Fields] < HI Factor[Fields] * Ref HI[Fields] , ((HIini[Fields] * Ref HI[Fields] * (Ref HI[Fields] - HIini[Fields]) * HIGC[Fields] * EXP (HIGC[Fields] * CGDD from flowering[Fields])) / (HIini[Fields] * (EXP (HIGC[Fields] * CGDD from flowering[Fields]) - 1) + Ref HI[Fields]) ^ 2) * conversion coefficient[Fields], (Ref HI[Fields] - HI Factor[Fields] * Ref HI[Fields]) / (length building up harvest index[Fields] - HI Lag period[Fields]) * conversion coefficient[Fields]) , IF THEN ELSE (crop type[Fields] = 3, ((HIini[Fields] * Ref HI[Fields] * (Ref HI[Fields] - HIini[Fields]) * HIGC[Fields] * EXP (HIGC[Fields] * CGDD from flowering[Fields])) / (HIini[Fields] * (EXP (HIGC[Fields] * CGDD from flowering[Fields]) - 1) + Ref HI[Fields]) ^ 2) * conversion coefficient[Fields], 0))) , 0)

404. helping matrix[l1,Fields] = Root water extraction flag[l1,Fields] + Root water extraction flag[l2,Fields] + Root water extraction flag[l3,Fields] + Root water extraction flag[l4,Fields] + Root water extraction flag[l5,Fields] + Root water extraction flag[l6,Fields] + Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
405. helping matrix[l2,Fields] = Root water extraction flag[l2,Fields] + Root water extraction flag[l3,Fields] + Root water extraction flag[l4,Fields] + Root water extraction flag[l5,Fields] + Root water extraction flag[l6,Fields] + Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]

406. helping matrix[l3,Fields] = Root water extraction flag[l3,Fields] + Root water extraction flag[l4,Fields] + Root water extraction flag[l5,Fields] + Root water extraction flag[l6,Fields] + Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + water extraction flag[l15,Fields]
407. helping matrix[l4,Fields] = Root water extraction flag[l4,Fields] + Root water extraction flag[l5,Fields] + Root water extraction flag[l6,Fields] + Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
408. helping matrix[l5,Fields] = Root water extraction flag[l5,Fields] + Root water extraction flag[l6,Fields] + Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
409. helping matrix[l6,Fields] = Root water extraction flag[l6,Fields] + Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
410. helping matrix[l7,Fields] = Root water extraction flag[l7,Fields] + Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]

411. helping matrix[l8,Fields] = Root water extraction flag[l8,Fields] + Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
412. helping matrix[l9,Fields] = Root water extraction flag[l9,Fields] + Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
413. helping matrix[l10,Fields] = Root water extraction flag[l10,Fields] + Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
414. helping matrix[l11,Fields] = Root water extraction flag[l11,Fields] + Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
415. helping matrix[l12,Fields] = Root water extraction flag[l12,Fields] + Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
416. helping matrix[l13,Fields] = Root water extraction flag[l13,Fields] + Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
417. helping matrix[l14,Fields] = Root water extraction flag[l14,Fields] + Root water extraction flag[l15,Fields]
418. helping matrix[l15,Fields] = Root water extraction flag[l15,Fields]
419. HI Lag period[Fields] = SAMPLE IF TRUE(Harvest Index stock[Fields] < 0.2 * Ref HI[Fields] , CGDD from flowering[Fields] , CGDD from flowering[Fields])
420. historic area rate = Historic irrigation Area * one week - delayed historic irrigation area * one week
421. historic conveyance[Conveyance] = historic conveyance LOOKUP[Conveyance] (simulation year)
422. historic conveyance rate[Conveyance] = historic conveyance[Conveyance] * one week - delayed conveyance[Conveyance] * one week

423. historic crop mix[Fields] = historic crop mix LOOKUP[Fields] (simulation year)
424. historic crop mix rate[Fields] = historic crop mix[Fields] * one week - delayed historic crop mix[Fields] * one week
425. Historic irrigation Area = historic irrigation area LOOKUP (simulation year)
426. historic irrigation technology[Irrigation Method] = historic irrigation technology LOOKUP[Irrigation Method] (simulation year)
427. historic technology rate[Irrigation Method] = historic irrigation technology[Irrigation Method] * one week - delayed technology[Irrigation Method] * one week
428. IED = SAMPLE IF TRUE(drain , Irrigation equivalent depth , 0)
429. Infiltration precipitation[Fields] = SUM (Precipitation rate[Fields,soil layers!] * Root zone layers activation flag[Fields,soil layers!])
430. Infrastructure expansion[Conveyance] = MAX (0, IF THEN ELSE (simulation year < simulation start year , historic conveyance rate[Conveyance] , IF THEN ELSE (simulation year <= conveyance target year + 1, infrastructure rate before target year[Conveyance] * per year to per week , 0)))
431. Infrastructure retirement[Conveyance] = MIN (IF THEN ELSE (simulation year < simulation start year , historic conveyance rate[Conveyance] , IF THEN ELSE (simulation year <= conveyance target year + 1, infrastructure rate before target year[Conveyance] * per year to per week , 0)) , 0) * -1
432. initial live storage input parameter = Initial live water storage constant * initial storage adjuster
433. Initial soil water content[soil layers,Fields] = soil layers TAW[Fields,soil layers] * modifier for initial conditions + soil layers PWP[soil layers,Fields]
434. Irrigation application[Fields] = Net Irrigation Requirement[Fields]
435. Irrigation application efficiency = SUM (Irrigation application technology[Irrigation Method!] * Irrigation application method efficiency[Irrigation Method!])
436. Irrigation by layer[l1,Fields] = MIN (Irrigation water to be applied[Fields] , Root zone layers depletion[l1,Fields] * irrigation depletion recharge switch + Depletion to saturation[l1,Fields] * (1 - irrigation depletion recharge switch))

437. Irrigation by layer[l2,Fields] = MIN (Root zone layers depletion[l2,Fields] * irrigation depletion recharge switch + Depletion to saturation[l2,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields])
438. Irrigation by layer[l3,Fields] = MIN (Root zone layers depletion[l3,Fields] * irrigation depletion recharge switch + Depletion to saturation[l3,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields])
439. Irrigation by layer[l4,Fields] = MIN (Root zone layers depletion[l4,Fields] * irrigation depletion recharge switch + Depletion to saturation[l4,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields])
440. Irrigation by layer[l5,Fields] = MIN (Root zone layers depletion[l5,Fields] * irrigation depletion recharge switch + Depletion to saturation[l5,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields])
441. Irrigation by layer[l6,Fields] = MIN (Root zone layers depletion[l6,Fields] * irrigation depletion recharge switch + Depletion to saturation[l6,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields])
442. Irrigation by layer[l7,Fields] = MIN (Root zone layers depletion[l7,Fields] * irrigation depletion recharge switch + Depletion to saturation[l7,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields])
443. Irrigation by layer[l8,Fields] = MIN (Root zone layers depletion[l8,Fields] * irrigation depletion recharge switch + Depletion to saturation[l8,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] -

Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields])

444. Irrigation by layer[l9,Fields] = MIN (Root zone layers depletion[l9,Fields] * irrigation depletion recharge switch + Depletion to saturation[l9,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields])
445. Irrigation by layer[l10,Fields] = MIN (Root zone layers depletion[l10,Fields] * irrigation depletion recharge switch + Depletion to saturation[l10,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields] - Irrigation by layer[l9,Fields])
446. Irrigation by layer[l11,Fields] = MIN (Root zone layers depletion[l11,Fields] * irrigation depletion recharge switch + Depletion to saturation[l11,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields] - Irrigation by layer[l9,Fields] - Irrigation by layer[l10,Fields])
447. Irrigation by layer[l12,Fields] = MIN (Root zone layers depletion[l12,Fields] * irrigation depletion recharge switch + Depletion to saturation[l12,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields] - Irrigation by layer[l9,Fields] - Irrigation by layer[l10,Fields] - Irrigation by layer[l11,Fields])

448. Irrigation by layer[l13,Fields] = MIN (Root zone layers depletion[l13,Fields] * irrigation depletion recharge switch + Depletion to saturation[l13,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields] - Irrigation by layer[l9,Fields] - Irrigation by layer[l10,Fields] - Irrigation by layer[l11,Fields] - Irrigation by layer[l12,Fields])

449. Irrigation by layer[l14,Fields] = MIN (Root zone layers depletion[l14,Fields] * irrigation depletion recharge switch + Depletion to saturation[l14,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields] - Irrigation by layer[l9,Fields] - Irrigation by layer[l10,Fields] - Irrigation by layer[l11,Fields] - Irrigation by layer[l12,Fields] - Irrigation by layer[l13,Fields])

450. Irrigation by layer[l15,Fields] = MIN (Root zone layers depletion[l15,Fields] * irrigation depletion recharge switch + Depletion to saturation[l15,Fields] * (1 - irrigation depletion recharge switch) , Irrigation water to be applied[Fields] - Irrigation by layer[l1,Fields] - Irrigation by layer[l2,Fields] - Irrigation by layer[l3,Fields] - Irrigation by layer[l4,Fields] - Irrigation by layer[l5,Fields] - Irrigation by layer[l6,Fields] - Irrigation by layer[l7,Fields] - Irrigation by layer[l8,Fields] - Irrigation by layer[l9,Fields] - Irrigation by layer[l10,Fields] - Irrigation by layer[l11,Fields] - Irrigation by layer[l12,Fields] - Irrigation by layer[l13,Fields] - Irrigation by layer[l14,Fields])

451. Irrigation equivalent depth = Total Water Withdrawal / Irrigation Area * cubic meter per ha to mm

452. Irrigation flag[Fields] = IF THEN ELSE (Root zone relative depletion[Fields] >= Irrigation threshold[Fields] , season flag[Fields] , 0) * (1 - scenescence trigger[Fields])

453. irrigation flag 2[Fields] = MAX (0, Irrigation flag[Fields] - delayed irrigation flag[Fields])
454. Irrigation per soil layer[soil layers,Barley] = Irrigation by layer[soil layers,Barley] / TIME STEP * Irrigate switch
455. Irrigation per soil layer[soil layers,Potato] = Irrigation by layer[soil layers,Potato] / TIME STEP * Irrigate switch
456. Irrigation per soil layer[soil layers,Wheat] = Irrigation by layer[soil layers,Wheat] / TIME STEP * Irrigate switch
457. Irrigation per soil layer[soil layers,Canola] = Irrigation by layer[soil layers,Canola] / TIME STEP * Irrigate switch
458. Irrigation per soil layer[soil layers,Sugar beet] = Irrigation by layer[soil layers,Sugar beet] / TIME STEP * Irrigate switch
459. Irrigation per soil layer[soil layers,Alfalfa] = Irrigation by layer[soil layers,Alfalfa] / TIME STEP * Irrigate switch
460. Irrigation per soil layer[soil layers,Barley Dryland] = 0
461. Irrigation per soil layer[soil layers,Potato Dryland] = 0
462. Irrigation per soil layer[soil layers,Wheat Dryland] = 0
463. Irrigation per soil layer[soil layers,Canola Dryland] = 0
464. Irrigation per soil layer[soil layers,Sugar beet Dryland] = 0
465. Irrigation per soil layer[soil layers,Alfalfa DryLand] = 0
466. Irrigation rate[Fields] = Total actual irrigation[Fields] / TIME STEP
467. Irrigation technology adoption rate[Irrigation Method] = MAX (0, IF THEN ELSE (simulation year < simulation start year , historic technology rate[Irrigation Method] , IF THEN ELSE (simulation year > irrigation technology target year + 1 :OR: Irrigation application efficiency > Target efficiency by target year , technology rate after target year[Irrigation Method] * per year to per week , technology rate before target year[Irrigation Method] * per year to per week))) * Decision score to adopt improved irrigation technologies
468. Irrigation technology retirement rate[Irrigation Method] = MIN (0, IF THEN ELSE (simulation year < simulation start year , historic technology rate[Irrigation Method] , IF THEN ELSE (simulation year > irrigation technology target year + 1 :OR: Irrigation application efficiency > Target efficiency by target year , technology rate after target year[Irrigation Method] * per year to per week , technology rate before target year[Irrigation Method] * per year to per week))) * -1 * Decision score to adopt improved irrigation technologies

469. irrigation threshold in terms of RAW[Fields] = Irrigation threshold[Fields] / Stomatal closure upper threshold depletion[Fields]
470. Irrigation water applied per hectare of crop at farm gate[Fields] = Net irrigation water applied per hectare of crop[Fields] / Irrigation application efficiency
471. irrigation water available per crop[Fields] = Irrigation water available per unit field[Fields] / Crop mix[Fields]
472. Irrigation water available per unit field[Fields] = ALLOCATE BY PRIORITY (Net field demand[Fields] , priority[Fields] , ELMCOUNT(Fields), priority width , Water storage supply above deficit level)
473. irrigation water deficit per field[Fields] = irrigation water available[Fields] - irrigation water required[Fields]
474. IWD = SAMPLE IF TRUE(drain , Total Water Withdrawal , 0)
475. Ke[Fields] = (1 - Adjusted Canopy Cover[Fields]) * Kex
476. Land economic index = weighted average contribution margin per hectare
477. Land productivity index = weighted average total crop yields per hectare
478. layer capacity for drainage storage[soil layers,Fields] = MAX (0, soil layers SAT[soil layers,Fields] - soil layers water content[soil layers,Fields])
479. LEI = SAMPLE IF TRUE(drain , Land economic index , 0)
480. live storage = irrigation districts owned storage + provincially owned storage
481. LPI = SAMPLE IF TRUE(drain , Land productivity index , 0)
482. Maximum temperature = LOOKUP BACKWARD (Tmax lookup , Time)
483. Minimum temperature = LOOKUP BACKWARD (Tmin lookup , Time)
484. Net field demand[Fields] = Net irrigation demand inflow[Fields] * TIME STEP * Crop mix[Fields] * irrigation depletion to optimum / 100
485. Net irrigation demand inflow[Fields] = IF THEN ELSE (Net Irrigation Requirement[Fields] - delayed net irrigation requirements[Fields] = Net Irrigation Requirement[Fields] :AND: Net Irrigation Requirement[Fields] <> 0, 1, 0) * Net Irrigation Requirement[Fields] / TIME STEP * season flag[Fields]
486. Net Irrigation Requirement[Fields] = Root zone depletion[Fields] * irrigation flag 2[Fields] * Flag for irrigated and dry lands[Fields]
487. Net irrigation water applied per hectare of crop[Fields] = Net Irrigation Water Applied[Fields] * mm to cubic meter per hectare

488. non water variable costs[Fields] = (crop insurance[Fields] + custom works and spec labor + fuel oil and lube[Fields] + labor[Fields] + operating interest + repairs[Fields] + seed fertilizers and chemicals[Fields] + storage[Fields] + trucking and marketing[Fields] + utilities[Fields])
489. per year to per week = 7 / 365
490. percentage applied of required = IF THEN ELSE (simulation year < simulation start year , 85, irrigation depletion to optimum)
491. PI = SAMPLE IF TRUE(drain , Profitability index , 0)
492. pivot flow rate = system capacity flow rate * pivot size
493. Potential evaporation[Fields] = Ke[Fields] * Reference Evapotranspiration * days to week
494. potential evaporation rate[Fields] = Potential evaporation[Fields]
495. potential maximum storage Smax[Fields] = 254 * (100 / Curve Number CN[Fields] - 1)
496. Precipitation = Area of resevoirs * unit mm km to cubic meter * Weekly Rainfall
497. Precipitation by layer[l1,Fields] = MIN (Effective precipitation events[Fields] , Depletion to saturation[l1,Fields])
498. Precipitation by layer[l2,Fields] = MIN (Depletion to saturation[l2,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields])
499. Precipitation by layer[l3,Fields] = MIN (Depletion to saturation[l3,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields])
500. Precipitation by layer[l4,Fields] = MIN (Depletion to saturation[l4,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields])
501. Precipitation by layer[l5,Fields] = MIN (Depletion to saturation[l5,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields])
502. Precipitation by layer[l6,Fields] = MIN (Depletion to saturation[l6,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] -

Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields])

503. Precipitation by layer[l7,Fields] = MIN (Depletion to saturation[l7,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields])
504. Precipitation by layer[l8,Fields] = MIN (Depletion to saturation[l8,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields])
505. Precipitation by layer[l9,Fields] = MIN (Depletion to saturation[l9,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields])
506. Precipitation by layer[l10,Fields] = MIN (Depletion to saturation[l10,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields] - Precipitation by layer[l9,Fields])
507. Precipitation by layer[l11,Fields] = MIN (Depletion to saturation[l11,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields] - Precipitation by layer[l9,Fields] - Precipitation by layer[l10,Fields])
508. Precipitation by layer[l12,Fields] = MIN (Depletion to saturation[l12,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] -

Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields] - Precipitation by layer[l9,Fields] - Precipitation by layer[l10,Fields] - Precipitation by layer[l11,Fields])

509. Precipitation by layer[l13,Fields] = MIN (Depletion to saturation[l13,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields] - Precipitation by layer[l9,Fields] - Precipitation by layer[l10,Fields] - Precipitation by layer[l11,Fields] - Precipitation by layer[l12,Fields])
510. Precipitation by layer[l14,Fields] = MIN (Depletion to saturation[l14,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields] - Precipitation by layer[l9,Fields] - Precipitation by layer[l10,Fields] - Precipitation by layer[l11,Fields] - Precipitation by layer[l12,Fields] - Precipitation by layer[l13,Fields])
511. Precipitation by layer[l15,Fields] = MIN (Depletion to saturation[l15,Fields] , Effective precipitation events[Fields] - Precipitation by layer[l1,Fields] - Precipitation by layer[l2,Fields] - Precipitation by layer[l3,Fields] - Precipitation by layer[l4,Fields] - Precipitation by layer[l5,Fields] - Precipitation by layer[l6,Fields] - Precipitation by layer[l7,Fields] - Precipitation by layer[l8,Fields] - Precipitation by layer[l9,Fields] - Precipitation by layer[l10,Fields] - Precipitation by layer[l11,Fields] - Precipitation by layer[l12,Fields] - Precipitation by layer[l13,Fields] - Precipitation by layer[l14,Fields])
512. Precipitation rate[Fields,soil layers] = MAX (0, Precipitation by layer[soil layers,Fields] / TIME STEP)
513. preset deficit level = provincial adjuster * provincially owned storage + district adjuster * irrigation districts owned storage
514. productivity index = SAMPLE IF TRUE(drain , productivity ratio , initial productivity ratio)

515. productivity ratio = ZIDZ (Aboveground Biomass[Barley] , Aboveground Biomass[Barley Dryland])
516. productivity score = productivity LOOKUP (productivity index)
517. Profitability index = ZIDZ (weighted average contribution margin per hectare , weighted average total crop yields per hectare)
518. Pumping cost[Fields] = Flag for irrigated and dry lands[Fields] * Average pumping KWh[Fields] * (electricity percentage * electricity rate + 0.0036 * natural gas percentage * natural gas rate) / pivot size
519. pumping hours required per pivot[Fields] = (Irrigation water applied per hectare of crop at farm gate[Fields] / 2.47105 * end of season stock drainage flag[Fields]) / (pivot flow rate / pivot size * 0.227125)
520. rainfall timer = MODULO (Time , 1)
521. Rainfall weekly event = IF THEN ELSE (rainfall timer , 0, 1) * Weekly Rainfall
522. rate 1[Fields] = irrigation water available per crop[Fields] / TIME STEP
523. rate 1 drain[Fields] = drain * irrigation water available[Fields] / TIME STEP
524. rate 2[Fields] = Net irrigation demand inflow[Fields] * irrigation depletion to optimum / 100
525. rate 2 drain[Fields] = drain * irrigation water required[Fields] / TIME STEP
526. rate of accumulation[Fields] = IF THEN ELSE (Canopy senescence water stress coefficient Kssen[Fields] < 0.9 :AND: season flag[Fields] , 1, 0)
527. ratio of withdrawal to licence = Withdrawal / Water licence allocation
528. Re initialization[soil layers,Fields] = start season[Fields] * Soil layers depletion[soil layers,Fields] / TIME STEP * 0.45
529. Readily evaporable water[Fields] = (field capacity water content ratio[l1,Fields] - Air dry soil water content ratio[l1,Fields]) * Zsurf[Fields]
530. Redistribution rate[l1,Fields] = 0
531. Redistribution rate[l2,Fields] = Drainage rate[l1,Fields]
532. Redistribution rate[l3,Fields] = Drainage rate[l2,Fields]
533. Redistribution rate[l4,Fields] = Drainage rate[l3,Fields]
534. Redistribution rate[l5,Fields] = Drainage rate[l4,Fields]
535. Redistribution rate[l6,Fields] = Drainage rate[l5,Fields]
536. Redistribution rate[l7,Fields] = Drainage rate[l6,Fields]
537. Redistribution rate[l8,Fields] = Drainage rate[l7,Fields]

538. Redistribution rate[l9,Fields] = Drainage rate[l8,Fields]
539. Redistribution rate[l10,Fields] = Drainage rate[l9,Fields]
540. Redistribution rate[l11,Fields] = Drainage rate[l10,Fields]
541. Redistribution rate[l12,Fields] = Drainage rate[l11,Fields]
542. Redistribution rate[l13,Fields] = Drainage rate[l12,Fields]
543. Redistribution rate[l14,Fields] = Drainage rate[l13,Fields]
544. Redistribution rate[l15,Fields] = Drainage rate[l14,Fields]
545. ref et in = Weekly evapotranspiration rate * season flag[Barley]
546. ref et out = drain * Cumulative Ref ET / TIME STEP
547. Ref HI[Fields] = (Increase in harvest index per decade[Fields] * (Time + 1) / 521.7 + HIo[Fields]) + HIo[Fields] * 0
548. Reference Evapotranspiration = IF THEN ELSE (Equation selector = 1, ET01 , IF THEN ELSE (Equation selector = 2, ET02 , IF THEN ELSE (Equation selector = 3, ET03 , ET04 using lookup)))
549. Relative depletion between upper and lower thresholds for canopy expansion[Fields] = ZIDZ (Adjusted depletion for canopy expansion[Fields] , Total available water between upper and lower thresholds for canopy expansion[Fields])
550. Relative depletion between upper and lower thresholds for canopy senescence[Fields] = ZIDZ (Adjusted depletion for canopy senescence[Fields] , Total available water between upper and lower thresholds for canopy senescence stress[Fields])
551. Relative depletion between upper and lower thresholds for stomatal closure[Fields] = ZIDZ (Adjusted depletion for stomatal closure[Fields] , Total available water between upper and lower thresholds for stomotal closure[Fields])
552. Relative nitrogen[Fields] = MAX (0, MIN (1, IF THEN ELSE (Time at which yield starts[Fields] = 0, 0, STEP (Nitrogen applied[Fields] , Time at which yield starts[Fields])) / Maximum nitrogen[Fields]))
553. Relative yield response to nitrogen[Fields] = coeff a[Fields] * Relative nitrogen[Fields] ^ 2 + coeff b[Fields] * Relative nitrogen[Fields] + coeff c[Fields]
554. repairs[Fields] = building repairs[Fields] + machinary repairs[Fields]
555. Residue accumulation[Fields] = Biomass accumulation rate[Fields] * (1 - Harvest Index[Fields])
556. Root growth[Fields] = IF THEN ELSE (Effective Rooting Depth[Fields] <= Maximum effective rooting depth Zx[Fields] , Stomatal closure water

stress coefficient Kssto[Fields] * (Maximum effective rooting depth Zx[Fields] - Sowing depth Zini[Fields]) * ZIDZ (((MAX (CGDD from sowing or transplanting[Fields] - Emergence or Recovery GDD[Fields] / 2, 0)) / (Maximum root depth GDD[Fields] - Emergence or Recovery GDD[Fields] / 2)) ^ (1 / ERD shape factor[Fields]) , (ERD shape factor[Fields] * (MAX (CGDD from sowing or transplanting[Fields] - Emergence or Recovery GDD[Fields] / 2, 0)))) * conversion coefficient[Fields] , 0)

557. Root water extraction flag[l1,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l1] , 1, 0)
558. Root water extraction flag[l2,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] , 1, 0)
559. Root water extraction flag[l3,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] , 1, 0)
560. Root water extraction flag[l4,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] , 1, 0)
561. Root water extraction flag[l5,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] , 1, 0)
562. Root water extraction flag[l6,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] , 1, 0)
563. Root water extraction flag[l7,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil

layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] , 1, 0)

564. Root water extraction flag[l8,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] , 1, 0)
565. Root water extraction flag[l9,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] , 1, 0)
566. Root water extraction flag[l10,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] + thickness of soil layers[Fields,l10] , 1, 0)
567. Root water extraction flag[l11,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] + thickness of soil layers[Fields,l10] + thickness of soil layers[Fields,l11] , 1, 0)
568. Root water extraction flag[l12,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] + thickness of soil layers[Fields,l10] +

thickness of soil layers[Fields,l11] + thickness of soil layers[Fields,l12] , 1, 0)

569. Root water extraction flag[l13,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] + thickness of soil layers[Fields,l10] + thickness of soil layers[Fields,l11] + thickness of soil layers[Fields,l12] + thickness of soil layers[Fields,l13] , 1, 0)
570. Root water extraction flag[l14,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] + thickness of soil layers[Fields,l10] + thickness of soil layers[Fields,l11] + thickness of soil layers[Fields,l12] + thickness of soil layers[Fields,l13] + thickness of soil layers[Fields,l14] , 1, 0)
571. Root water extraction flag[l15,Fields] = IF THEN ELSE (Effective rooting depth adjusted[Fields] * mm to m >= thickness of soil layers[Fields,l3] + thickness of soil layers[Fields,l1] + thickness of soil layers[Fields,l2] + thickness of soil layers[Fields,l4] + thickness of soil layers[Fields,l5] + thickness of soil layers[Fields,l6] + thickness of soil layers[Fields,l7] + thickness of soil layers[Fields,l8] + thickness of soil layers[Fields,l9] + thickness of soil layers[Fields,l10] + thickness of soil layers[Fields,l11] + thickness of soil layers[Fields,l12] + thickness of soil layers[Fields,l13] + thickness of soil layers[Fields,l14] + thickness of soil layers[Fields,l15] , 1, 0)
572. Root zone depletion[Fields] = MAX (0, Root zone field capacity[Fields] - Root zone water content[Fields])
573. Root zone field capacity[Fields] = SUM (field capacity water content ratio[soil layers!,Fields] * thickness of soil layers[Fields,soil layers!] * Root water extraction flag[soil layers!,Fields])

574. Root zone layers depletion[soil layers,Fields] = Root water extraction flag[soil layers,Fields] * Soil layers depletion[soil layers,Fields]
575. Root zone layers TAW[soil layers,Fields] = (soil layers FC[soil layers,Fields] - soil layers PWP[soil layers,Fields]) * Root water extraction flag[soil layers,Fields]
576. Root zone layers water content[soil layers,Fields] = Root water extraction flag[soil layers,Fields] * soil layers water content[soil layers,Fields]
577. Root zone permenant wilting point[Fields] = SUM (permenant wilting point water content ratio[soil layers!,Fields] * thickness of soil layers[Fields,soil layers!] * Root water extraction flag[soil layers!,Fields])
578. Root zone relative depletion[Fields] = ZIDZ (Root zone depletion[Fields] , Root zone TAW[Fields])
579. Root zone saturation[Fields] = SUM (saturation water content[soil layers!,Fields] * thickness of soil layers[Fields,soil layers!] * Root water extraction flag[soil layers!,Fields])
580. Root zone TAW[Fields] = SUM (Root zone layers TAW[soil layers!,Fields])
581. Root zone water content[Fields] = SUM (Root zone layers water content[soil layers!,Fields])
582. Runoff[Fields] = MAX (0, IF THEN ELSE (Rainfall weekly event <= 0.2 * potential maximum storage Smax[Fields] , 0, (Rainfall weekly event - 0.2 * potential maximum storage Smax[Fields]) ^ 2 / (Rainfall weekly event + potential maximum storage Smax[Fields] - 0.2 * potential maximum storage Smax[Fields])))
583. RZ layers WC ratio[soil layers,Fields] = Root zone layers water content[soil layers,Fields] / thickness of soil layers[Fields,soil layers]
584. RZ WC ratio[Fields] = SUM (RZ layers WC ratio[soil layers!,Fields]) / sum of layers[Fields]
585. scenescence trigger[Fields] = IF THEN ELSE (CGDD from sowing or transplanting[Fields] >= Senescence GDD[Fields] :OR: (senescence trigger accumulator[Fields] >= trigger factor :AND: CGDD from sowing or transplanting[Fields] >= Maximum canopy GDD[Fields] / 2) , 1, 0)
586. season flag[Fields] = start of season flag[Fields] * (1 - end of season stock drainage flag[Fields])
587. season in[Fields] = start season[Fields]

588. season out[Fields] = drain * start of season stock[Fields] / TIME STEP
589. seed fertilizers and chemicals[Fields] = chemicals[Fields] + fertilizers[Fields] + seed[Fields]
590. simulation year = simulation year LOOKUP (Time)
591. soil layers AD[soil layers,Fields] = Air dry soil water content ratio[soil layers,Fields] * thickness of soil layers[Fields,soil layers]
592. Soil layers depletion[soil layers,Fields] = MAX (0, soil layers FC[soil layers,Fields] - soil layers water content[soil layers,Fields])
593. soil layers FC[soil layers,Fields] = field capacity water content ratio[soil layers,Fields] * thickness of soil layers[Fields,soil layers]
594. soil layers PWP[soil layers,Fields] = permenant wilting point water content ratio[soil layers,Fields] * thickness of soil layers[Fields,soil layers]
595. soil layers SAT[soil layers,Fields] = saturation water content[soil layers,Fields] * thickness of soil layers[Fields,soil layers]
596. soil layers TAW[Fields,soil layers] = soil layers FC[soil layers,Fields] - soil layers PWP[soil layers,Fields]
597. soil layers water content ratio[soil layers,Fields] = soil layers water content[soil layers,Fields] / thickness of soil layers[Fields,soil layers]
598. Soil profile depletion[soil layers,Fields] = MAX (0, (soil layers FC[soil layers,Fields] - soil layers water content[soil layers,Fields]))
599. soil profile field capacity[Fields] = SUM (soil layers FC[soil layers!,Fields] * Root zone layers activation flag[Fields,soil layers!])
600. soil profile permenant wilting point[Fields] = SUM (Root zone layers activation flag[Fields,soil layers!] * soil layers PWP[soil layers!,Fields])
601. Soil profile relative depletion[Fields] = SUM (Soil profile depletion[soil layers!,Fields] / TAW of soil profile[soil layers!,Fields]) / SUM (Root zone layers activation flag[Fields,soil layers!])
602. soil profile saturation[Fields] = SUM (Root zone layers activation flag[Fields,soil layers!] * soil layers SAT[soil layers!,Fields])
603. Soil profile total depletion[Fields] = SUM (Soil profile depletion[soil layers!,Fields])
604. Soil Water Content[Fields] = SUM (soil layers water content[soil layers!,Fields] * Root zone layers activation flag[Fields,soil layers!])

605. Spill off = IF THEN ELSE (Live Water Storage >= total live water storage , (Live Water Storage - total live water storage) , 0)

606. start of season flag[Fields] = IF THEN ELSE (start of season stock[Fields] , 1, 0)

607. start season[Fields] = IF THEN ELSE (MODULO (start season flag LOOKUP (Time) , 1) = 0, 1, 0)

608. Stomatal closure water stress coefficient Kssto[Fields] = IF THEN ELSE (Root zone relative depletion[Fields] <= Stomatal closure upper threshold depletion[Fields] , 1, IF THEN ELSE (Root zone relative depletion[Fields] > Stomatal closure lower threshold depletion[Fields] , 0, Linear or convex for stomatal closure * (1 - ((EXP (stomatal control shape factor[Fields] * Relative depletion between upper and lower thresholds for stomatal closure[Fields]) - 1) / (EXP (stomatal control shape factor[Fields]) - 1))) + (1 - Relative depletion between upper and lower thresholds for stomatal closure[Fields]) * (1 - Linear or convex for stomatal closure)))

609. storage flag = storage flag LOOKUP (Time)

610. streamflow input = streamflow LOOKUP (Time)

611. Streamflow rate = streamflow input * (1 - Water Conservation Objectives) * (1 - Instream flow needs IFN)

612. sum of layers[Fields] = SUM (Root water extraction flag[soil layers!,Fields])

613. SWC ratio[Fields] = SUM (soil layers water content ratio[soil layers!,Fields]) / 15

614. SWC rel[Fields] = MAX (0, (((soil layers water content[l1,Fields] - soil layers AD[l1,Fields]) / (soil layers SAT[l1,Fields] - soil layers AD[l1,Fields])) + ((soil layers water content[l2,Fields] - soil layers AD[l2,Fields]) / (soil layers SAT[l2,Fields] - soil layers AD[l2,Fields])) + ((soil layers water content[l3,Fields] - soil layers AD[l3,Fields]) / (soil layers SAT[l3,Fields] - soil layers AD[l3,Fields]))) / 3)

615. Tavg = (MAX (Maximum temperature + Temperature adjustment lever , 0) + (Minimum temperature + Temperature adjustment lever)) / 2

616. Tavg adjusted[Fields] = IF THEN ELSE (Average temperature[Fields] < Base temperature[Fields] , Base temperature[Fields] , Average temperature[Fields])

617. TAW of soil profile[soil layers,Fields] = soil layers FC[soil layers,Fields] - soil layers PWP[soil layers,Fields]
618. TCM = SUM (Contribution margin[Fields!] * Crop mix[Fields!]) * Irrigation Area
619. Tdiff = MAX (Maximum temperature + Temperature adjustment lever , 0) - (Minimum temperature + Temperature adjustment lever)
620. Temperature biomass stress Ks[Fields] = IF THEN ELSE (Temperature stress effect on biomass switch = 1, IF THEN ELSE (Growing Degree Days[Fields] < Minimum GDD upper threshold[Fields] , 1 / (1 + EXP (- (Growing Degree Days[Fields] - Minimum GDD upper threshold[Fields] / 2))) , 1) , 1)
621. Time at which yield starts[Fields] = SAMPLE IF TRUE(:NOT: Time at which yield starts[Fields] :AND: CGDD from sowing or transplanting[Fields] >= Start of yield and building up HI GDD[Fields] , Time , 0)
622. Time rate 2[Fields] = IF THEN ELSE (:NOT: end of season stock drainage flag[Fields] :AND: CGDD from sowing or transplanting[Fields] >= Maximum canopy GDD[Fields] , 1, 0)
623. Tmax adjusted[Fields] = IF THEN ELSE (Maximum temperature + Temperature adjustment lever >= Upper temperature[Fields] , Upper temperature[Fields] , IF THEN ELSE (Maximum temperature + Temperature adjustment lever < Base temperature[Fields] , Base temperature[Fields] , Maximum temperature + Temperature adjustment lever))
624. Tmin adjusted[Fields] = IF THEN ELSE (Minimum temperature + Temperature adjustment lever > Upper temperature[Fields] , Upper temperature[Fields] , Minimum temperature + Temperature adjustment lever)
625. Total actual irrigation[Fields] = SUM (Irrigation per soil layer[soil layers!,Fields]) * TIME STEP
626. total area of each field[Fields] = Irrigation Area * Crop mix[Fields] * Flag for irrigated and dry lands[Fields]
627. total area of each field at the start of the season[Fields] = total area of each field[Fields]
628. Total available water between upper and lower thresholds for canopy expansion[Fields] = (Canopy expansion lower depletion threshold[Fields] - Canopy expansion upper depletion threshold[Fields]) * Root zone TAW[Fields]
629. Total available water between upper and lower thresholds for canopy senescence stress[Fields] = (Canopy threshold lower threshold

depletion[Fields] - Canopy senescence upper threshold depletion[Fields]) * Root zone TAW[Fields]

630. Total available water between upper and lower thresholds for stomotal closure[Fields] = (Stomatal closure lower threshold depletion[Fields] - Stomatal closure upper threshold depletion[Fields]) * Root zone TAW[Fields]
631. Total expenses = SAMPLE IF TRUE(drain , (Expenses[Barley] + Expenses[Potato] + Expenses[Wheat] + Expenses[Canola] + Expenses[Sugar beet] + Expenses[Alfalfa]) / 6, 0)
632. Total gross irrigation applied at farm gates = SUM (gross irrigation water applied per field[Fields!])
633. Total gross irrigation applied at headworks = Total gross irrigation applied at farm gates / Conveyance system efficiency
634. Total gross irrigation water demand at farm gate = SUM (Field gross irrigation water demand at farm gate[Fields!])
635. Total gross irrigation water demand at headworks = Total gross irrigation water demand at farm gate / Conveyance system efficiency
636. total live water storage = IF THEN ELSE (simulation year >= start year of construction + construction lag in years , live storage * (1 + percentage increase in storage / 100) , live storage)
637. total water supply rate = storage flag * Streamflow rate
638. transpiration by layer[soil layers,Fields] = helping matrix[soil layers,Fields] / (sum of layers[Fields] * (sum of layers[Fields] + 1) / 2) * Transpiration demand[Fields] * Stomatal closure water stress coefficient Kssto[Fields]
639. Transpiration demand[Fields] = Crop transpiration coefficient Kctr[Fields] * Weekly Reference Evapotranspiration
640. Transpiration rate[soil layers,Fields] = IF THEN ELSE (soil layers water content[soil layers,Fields] <= 0, 0, transpiration by layer[soil layers,Fields])
641. trigger factor = IF THEN ELSE (TIME STEP = 1, TIME STEP , IF THEN ELSE (TIME STEP = 0.5, TIME STEP , scenescence trigger multiplier))
642. Water available to apply per irrigation event[Fields] = IF THEN ELSE (Water supply major feedback ON OFF = 1, IF THEN ELSE (Irrigate switch = 0, 0, MIN (Irrigation application[Fields] , irrigation water available per crop[Fields])) , IF THEN ELSE (Irrigate switch = 0, 0, Irrigation application[Fields]))

643. water demand risk index = ratio of withdrawal to licence
644. water demand risk score = water supply reliability LOOKUP (water demand risk index)
645. Water economic index = ZIDZ (weighted average contribution margin per hectare , weighted average total gross irrigation applied per hectare at headworks)
646. water horsepower required[Irrigation Method] = pump operating pressure[Irrigation Method] * pivot flow rate / (1715 * pump efficiency)
647. water potential deficit = MIN (0, Live Water Storage - irrigation depletion to optimum / 100 * Total gross irrigation water demand at headworks) * IF THEN ELSE (Live Water Storage <= preset deficit level , 1, 0)
648. Water Productivity Adjusted[Fields] = Water Productivity WP[Fields] / gm per sqm to t per ha * fco2
649. Water productivity index = ZIDZ (weighted average total crop yields per hectare , weighted average total gross irrigation applied per hectare at headworks) * ton to kg
650. Water scarcity index = ZIDZ (Total Water Withdrawal , Water licence allocation)
651. Water scarcity index 2 = ZIDZ (Total Water Withdrawal * Total Water Withdrawal , Total Water Streamflow * Water licence allocation)
652. Water shortage = ((water potential deficit * -1) / Irrigation Area) * 1 / mm to cubic meter per hectare
653. water storage supply = MAX (0, Live Water Storage - preset deficit level)
654. Water storage supply above deficit level = MAX (0, (Live Water Storage - preset deficit level) / Irrigation Area * 1 / mm to cubic meter per hectare)
655. Weekly evapotranspiration rate = Weekly Reference Evapotranspiration
656. Weekly Growing Degrees[Fields] = Growing Degree Days[Fields] * 7
657. weekly rain = Weekly Rainfall * season flag[Barley]
658. Weekly Rainfall = LOOKUP BACKWARD (Weekly Rainfall LOOKUP , Time)
659. Weekly Reference Evapotranspiration = Reference Evapotranspiration * days to week
660. WEI = SAMPLE IF TRUE(drain , Water economic index , 0)

661. weighted average contribution margin per hectare = MAX (Contribution margin[Barley] * Crop mix[Barley] + Contribution margin[Potato] * Crop mix[Potato] + Contribution margin[Wheat] * Crop mix[Wheat] + Contribution margin[Canola] * Crop mix[Canola] + Contribution margin[Sugar beet] * Crop mix[Sugar beet] + Contribution margin[Alfalfa] * Crop mix[Alfalfa] , 0)
662. weighted average field gross irrigation applied per hectare at farm gates[Fields] = mm to cubic meter per hectare * Net Irrigation Water Applied[Fields] * Crop mix[Fields] / Irrigation application efficiency
663. weighted average total crop yields per hectare = Dry matter crop yield[Barley] * Crop mix[Barley] + Dry matter crop yield[Potato] * Crop mix[Potato] + Dry matter crop yield[Wheat] * Crop mix[Wheat] + Dry matter crop yield[Canola] * Crop mix[Canola] + Dry matter crop yield[Sugar beet] * Crop mix[Sugar beet] + Dry matter crop yield[Alfalfa] * Crop mix[Alfalfa]
664. weighted average total gross irrigation applied per hectare at headworks = SUM (weighted average field gross irrigation applied per hectare at farm gates[Fields!]) / Conveyance system efficiency
665. weighting factor = 1 - ((550 - Actual CO2) / (550 - Reference CO2))
666. Withdrawal = SAMPLE IF TRUE(drain , Total Water Withdrawal , reference demand value)
667. WPI = SAMPLE IF TRUE(drain , Water productivity index , 0)
668. WSI = SAMPLE IF TRUE(drain , Water scarcity index , 0)
669. WSI2 = SAMPLE IF TRUE(drain , Water scarcity index 2 , 0)

Model Variable Units

- Aboveground Biomass - Units: t/ha
- access to incentive and subsidies LOOKUP - Units: Dmnl
- access to incentives score - Units: Dmnl
- Actual CO2 - Units: ppm
- Actual evaporation - Units: mm/week
- actual evaporation rate - Units: mm/week
- actual evapotranspiration rate - Units: mm/week
- Actual transpiration - Units: mm/week
- actual transpiration rate - Units: mm/week

- Adjusted Canopy Cover - Units: Dmnl
- Adjusted CDC - Units: 1/degree day
- Adjusted CGC - Units: 1/degree day
- Adjusted depletion for canopy expansion - Units: mm
- Adjusted depletion for canopy senescence - Units: mm
- Adjusted depletion for stomatal closure - Units: mm
- Adjusted Kctrx - Units: Dmnl
- Air dry soil water content ratio - Units: Dmnl
- annual deficit flag - Units: Dmnl
- Area Expansion - Units: ha/week
- Area of reservoirs - Units: km2
- Aridity Index - Units: Dmnl
- aridity index LOOKUP - Units: Dmnl
- aridity index score - Units: Dmnl
- Average pumping KWh - Units: kWh/pivot
- Average temperature - Units: degreeC
- Base temperature - Units: degreeC
- bface - Units: Dmnl
- Biomass accumulation rate - Units: t/(week*ha)
- Biomass formation flag - Units: Dmnl
- BM - Units: t/ha
- bsted - Units: Dmnl
- building repairs - Units: $/acre
- Canopy Cover - Units: Dmnl
- Canopy cover flag - Units: Dmnl
- Canopy Cover Stock - Units: Dmnl
- canopy decay max - Units: 1/week
- Canopy decay rate - Units: 1/week
- Canopy development water stress coefficient Ksexp - Units: Dmnl
- Canopy expansion lower depletion threshold - Units: Dmnl
- canopy expansion shape factor - Units: Dmnl
- Canopy expansion upper depletion threshold - Units: Dmnl
- Canopy in exp decay rate - Units: 1/week

- Canopy in exp growth rate - Units: 1/week
- Canopy level - Units: 1/week
- canopy out adjusted - Units: 1/week
- canopy senescence stress shape factor - Units: Dmnl
- Canopy senescence upper threshold depletion - Units: Dmnl
- Canopy senescence water stress coefficient Kssen - Units: Dmnl
- Canopy threshold lower threshold depletion - Units: Dmnl
- CC0 - Units: Dmnl
- CCx - Units: Dmnl
- CDC - Units: 1/degree day
- CGC - Units: 1/degree day
- CGDD flag - Units: Dmnl
- CGDD from emergence or recovering - Units: degree day
- CGDD from flowering - Units: degree day
- CGDD from senescence - Units: degree day
- CGDD from sowing or transplanting - Units: degree day
- chemicals - Units: $/acre
- clear residue - Units: t/(week*ha)
- CO2 lookup - Units: ppm
- coeff a - Units: Dmnl
- coeff b - Units: Dmnl
- coeff c - Units: Dmnl
- construction lag in years - Units: year
- Contribution margin - Units: $/ha
- conversion coefficient - Units: degree day/week
- Conveyance -
- Conveyance infrastructure length - Units: km
- conveyance infrastructure length capacity - Units: km
- Conveyance system efficiency - Units: Dmnl
- Conveyance system method efficiency - Units: Dmnl
- conveyance target year - Units: year
- Correction factor - Units: Dmnl
- crop insurance - Units: $/acre

- Crop mix - Units: Dmnl
- crop mix change rate - Units: 1/year
- Crop price LOOKUP - Units: $/t
- Crop residue in soil - Units: t/ha
- Crop revenue per hectare - Units: $/ha
- Crop selling price per ton - Units: $/t
- Crop transpiration coefficient Kctr - Units: Dmnl
- crop type - Units: Dmnl
- Crops adding rate - Units: 1/week
- Crops retiring rate - Units: 1/week
- cubic meter per ha to mm - Units: mm/m3
- Cumulative Actual Evaporation - Units: mm
- Cumulative Actual Evapotranspiration - Units: mm
- Cumulative Actual Transpiration - Units: mm
- Cumulative growing degree days - Units: degree day
- Cumulative Potential Evaporation - Units: mm
- Cumulative precipitation - Units: mm
- Cumulative Ref ET - Units: mm
- Cumulative Reference Evapotranspiration - Units: mm
- Curve Number CN - Units: Dmnl
- custom works and spec labor - Units: $/acre
- CY - Units: t/ha
- days to week - Units: Day/week
- Decision score to adopt improved irrigation technologies - Units: Dmnl
- Decision score to expand irrigation area - Units: Dmnl
- decline factor fk - Units: Dmnl
- Deep percolated precipitation - Units: mm
- Deep percolation - Units: mm
- deep percolation rate - Units: mm/week
- Deficit counter - Units: Dmnl
- deficit counter rate - Units: 1/week
- deficit delayed - Units: **undefined**
- deficit drain - Units: 1/week

- deficit flag - Units: Dmnl
- deficit irrigation application - Units: Dmnl
- degreeC to degree day - Units: degree day/degreeC
- delay fixed canopy decay max - Units: 1/week
- delay for irrigation - Units: Day
- delayed CGDD - Units: degree day
- delayed conveyance - Units: km
- delayed historic crop mix - Units: Dmnl
- delayed historic irrigation area - Units: ha
- delayed irrigation flag - Units: Dmnl
- delayed net irrigation requirements - Units: mm
- delayed technology - Units: Dmnl
- Delta - Units: kPa/degreeC
- Demand Withdrawal - Units: m3/week
- Depletion to saturation - Units: mm
- district adjuster - Units: Dmnl
- Diversion to Storage - Units: m3/week
- drain - Units: Dmnl
- drain actual evaporation - Units: mm/week
- Drain Biomass Stock - Units: t/(week*ha)
- drain canopy stock - Units: 1/week
- Drain CGDD stock 2 - Units: degree day/week
- drain cpe - Units: mm/week
- drain deep percolated precipitation stock - Units: mm/week
- drain ERD stock - Units: m/week
- drain HI stock - Units: 1/degree day
- drain net irrigation water applied stock - Units: mm/week
- drain net irrigation water demand stock - Units: mm/(week*m2)
- drain rain - Units: mm/week
- Drain stock - Units: 1/week
- Drain stock 1 - Units: degree day/week
- Drain stock 2 - Units: degree day/week
- Drain stock 3 - Units: degree day/week

- Drain stock 5 - Units: degree day/week
- drain streamflow supply stock - Units: m3/week
- Drain time stock 2 - Units: 1
- drain total demand stock - Units: m3/week
- drain water supply stock - Units: m3/week
- Drainage by layer using Aquacrop approach - Units: mm
- drainage characteristic tau - Units: Dmnl
- drainage function - Units: 1/week
- Drainage rate - Units: mm/week
- Drainge - Units: mm/week
- Drainge by layer using AquaCrop approach with maximum allowable storage - Units:
- mm
- Dry matter crop yield - Units: t/ha
- Dry matter crop yield with fertilizer - Units: t/ha
- ea - Units: kPa
- Effective precipitation events - Units: mm
- Effective Rooting Depth - Units: m
- Effective rooting depth adjusted - Units: m
- electricity percentage - Units: Dmnl
- electricity rate - Units: $/kWh
- Emergence or Recovery GDD - Units: degree day
- end of season stock drainage flag - Units: Dmnl
- Equation selector - Units: Dmnl
- ERD shape factor - Units: Dmnl
- es - Units: kPa
- ET01 - Units: mm/Day
- ET02 - Units: mm/Day
- ET03 - Units: mm/Day
- ET04 - Units: mm/Day
- ET04 lookup - Units: mm/Day
- ET04 using lookup - Units: mm/Day
- Evaporation - Units: m3/week

- Evaporation rate - Units: mm/week
- Evaporation rate from top layer - Units: mm/week
- Evaporation reduction coefficient Kr - Units: Dmnl
- excess drainage water - Units: mm
- expansion rate - Units: ha/year
- Expenses - Units: $/ha
- expontent coefficient a - Units: Dmnl
- extension service LOOKUP - Units: Dmnl
- extension services score - Units: Dmnl
- Extraterrestrial rad Ra - Units: MJ/(Day*m2)
- factor - Units: Dmnl
- fage - Units: 1/week
- fco2 - Units: **undefined**
- fertilizers - Units: $/acre
- field capacity water content ratio - Units: Dmnl
- Field gross irrigation water applied at farm gate - Units: m3
- Field gross irrigation water demand at farm gate - Units: m3
- Field gross irrigation water demand per hectare at farm gate - Units: m3/ha
- Fields -
- FINAL TIME - Units: week
- Flag for irrigated and dry lands - Units: Dmnl
- fsen - Units: Dmnl
- fsink - Units: Dmnl
- fuel oil and lube - Units: $/acre
- GDD Inflow - Units: degree day/week
- GDD Rate from emergence - Units: degree day/week
- GDD Rate from flowering - Units: degree day/week
- GDD Rate from planting - Units: degree day/week
- GDD Rate from Senescence - Units: degree day/week
- gm per sqm to t per ha - Units: gm/(ha*t*m2)
- gross irrigation water applied per field - Units: m3
- gross total irrigation water applied at headworks - Units: m3/ha

- Growing Degree Days - Units: degree day
- Harvest Index - Units: Dmnl
- Harvest index out - Units: 1/degree day
- Harvest Index Rate - Units: 1/degree day
- Harvest Index stock - Units: Dmnl
- helping matrix - Units: Dmnl
- HI Factor - Units: Dmnl
- HI Lag period - Units: degree day
- HIGC - Units: 1/degree day
- HIini - Units: Dmnl
- HIo - Units: Dmnl
- historic area rate - Units: ha/week
- historic conveyance - Units: km
- historic conveyance LOOKUP - Units: Dmnl
- historic conveyance rate - Units: km/week
- historic crop mix - Units: Dmnl
- historic crop mix LOOKUP - Units: Dmnl
- historic crop mix rate - Units: 1/week
- Historic irrigation Area - Units: ha
- historic irrigation area LOOKUP - Units: ha
- historic irrigation technology - Units: Dmnl
- historic irrigation technology LOOKUP - Units: Dmnl
- historic technology rate - Units: 1/year
- IED - Units: mm/ha
- Increase in harvest index per decade - Units: 1/decade
- Infiltration precipitation - Units: mm
- Infrastructure expansion - Units: km/week
- infrastructure rate before target year - Units: km/year
- Infrastructure retirement - Units: km/week
- initial live storage input parameter - Units: m3
- Initial live water storage constant - Units: m3
- Initial plant coverage - Units: cm2/plant
- initial productivity ratio - Units: Dmnl

- Initial soil water content - Units: mm
- initial storage adjuster - Units: Dmnl
- INITIAL TIME - Units: week
- Instream flow needs IFN - Units: Dmnl
- Irrigate switch - Units: Dmnl
- Irrigation application - Units: mm
- Irrigation application efficiency - Units: Dmnl
- Irrigation application method efficiency - Units: Dmnl
- Irrigation application technology - Units: Dmnl
- irrigation applied to optimum - Units: Dmnl
- Irrigation Area - Units: ha
- irrigation area year limit - Units: year
- Irrigation by layer - Units: mm
- irrigation depletion recharge switch - Units: Dmnl
- irrigation districts owned storage - Units: m3
- Irrigation equivalent depth - Units: mm/ha
- Irrigation flag - Units: Dmnl
- irrigation flag 2 - Units: Dmnl
- Irrigation Method -
- Irrigation per soil layer - Units: mm/week
- Irrigation rate - Units: mm/week
- Irrigation technology adoption rate - Units: 1/year
- Irrigation technology retirement rate - Units: 1/year
- irrigation technology target year - Units: year
- Irrigation threshold - Units: Dmnl
- irrigation threshold in terms of RAW - Units: Dmnl
- Irrigation water applied per hectare of crop at farm gate - Units: m3/ha
- irrigation water available - Units: mm
- irrigation water available per crop - Units: mm
- Irrigation water available per unit field - Units: mm
- irrigation water deficit per field - Units: mm
- irrigation water required - Units: mm
- Irrigation water to be applied - Units: mm

- IWD - Units: m3
- Ke - Units: Dmnl
- Kex - Units: Dmnl
- Ksat - Units: mm/Day
- labor - Units: $/acre
- lag of improved irrigation scheduling - Units: Day
- Land economic index - Units: $/ha
- Land productivity index - Units: t/ha
- layer capacity for drainage storage - Units: mm
- LEI - Units: $/ha
- length building up harvest index - Units: degree day
- Linear of convex for canopy development - Units: Dmnl
- Linear or convex for stomatal closure - Units: Dmnl
- live storage - Units: m3
- Live Water Storage - Units: m3
- LPI - Units: t/ha
- machinary repairs - Units: $/acre
- Maturity GDD end of yield - Units: degree day
- Maximum canopy GDD - Units: degree day
- Maximum crop transpiration coefficient Kctrx - Units: Dmnl
- Maximum effective rooting depth Zx - Units: m
- Maximum nitrogen - Units: kgN/ha
- Maximum root depth GDD - Units: degree day
- Maximum temperature - Units: degreeC
- Minimum effective rooting depth Zn - Units: m
- Minimum GDD upper threshold - Units: degree day
- Minimum growing degrees for full biomass production - Units: degree day
- Minimum temperature - Units: degreeC
- mm to cubic meter per hectare - Units: m3/(mm*ha)
- mm to m - Units: mm/m
- modifier for initial conditions - Units: Dmnl
- moisture ratio for crops - Units: Dmnl
- motor efficiency - Units: Dmnl

- natural gas percentage - Units: Dmnl
- natural gas rate - Units: $/GJ
- Net field demand - Units: mm
- Net irrigation demand inflow - Units: mm/week
- Net Irrigation Requirement - Units: mm
- Net Irrigation Water Applied - Units: mm
- Net irrigation water applied per hectare of crop - Units: m3/ha
- Net Irrigation Water Demand - Units: mm
- new storage - Units: m3
- Nitrogen applied - Units: kgN/ha
- non water variable costs - Units: $/acre
- Number of plants per hectare - Units: plants/hectare
- one week - Units: 1/week
- operating interest - Units: $/acre
- per acre to per hectare - Units: acre/ha
- per year to per week - Units: year/week
- percentage applied of required - Units: Dmnl
- percentage increase in storage - Units: Dmnl
- permenant wilting point water content ratio - Units: Dmnl
- PI - Units: $/t
- pivot flow rate - Units: gpm/pivot
- pivot size - Units: acre
- Potential evaporation - Units: mm/Day
- potential evaporation rate - Units: mm/week
- potential maximum storage Smax - Units: mm
- Precipitation - Units: m3/week
- Precipitation by layer - Units: mm
- Precipitation rate - Units: mm/week
- preset deficit level - Units: m3
- priority - Units: Dmnl
- priority width - Units: Dmnl
- productivity index - Units: Dmnl
- productivity LOOKUP - Units: Dmnl

- productivity ratio - Units: Dmnl
- productivity score - Units: Dmnl
- Profitability index - Units: $/t
- provincial adjuster - Units: Dmnl
- provincially owned storage - Units: m3
- pump efficiency - Units: Dmnl
- pump operating pressure - Units: psi
- Pumping cost - Units: $/acre
- pumping hours required per pivot - Units: hr/pivot
- rainfall timer - Units: Dmnl
- Rainfall weekly event - Units: mm/week
- rate 1 - Units: mm/week
- rate 1 drain - Units: mm/week
- rate 2 - Units: mm/week
- rate 2 drain - Units: mm/week
- rate of accumulation - Units: 1/week
- ratio of withdrawal to licence - Units: Dmnl
- Re initialization - Units: mm/week
- Readily evaporable water - Units: mm
- Redistribution rate - Units: mm/week
- ref et in - Units: mm/week
- ref et out - Units: mm/week
- Ref HI - Units: Dmnl
- Reference CO2 - Units: ppm
- reference demand value - Units: m3
- Reference Evapotranspiration - Units: mm/Day
- relative access to incentives - Units: Dmnl
- Relative depletion between upper and lower thresholds for canopy expansion -
- Units: Dmnl
- Relative depletion between upper and lower thresholds for canopy senescence -
- Units: Dmnl

- Relative depletion between upper and lower thresholds for stomatal closure -
- Units: Dmnl
- relative extension visits and education - Units: Dmnl
- Relative humidity - Units: Percentage
- Relative nitrogen - Units: Dmnl
- Relative yield response to nitrogen - Units: Dmnl
- repairs - Units: $/acre
- Residue accumulation - Units: t/(week*ha)
- Root growth - Units: m/week
- Root water extraction flag - Units: Dmnl
- Root zone depletion - Units: mm
- Root zone field capacity - Units: mm
- Root zone layers activation flag - Units: Dmnl
- Root zone layers depletion - Units: mm
- Root zone layers TAW - Units: mm
- Root zone layers water content - Units: mm
- Root zone permenant wilting point - Units: mm
- Root zone relative depletion - Units: Dmnl
- Root zone saturation - Units: mm
- Root zone TAW - Units: mm
- Root zone water content - Units: mm
- Runoff - Units: mm
- RZ layers WC ratio - Units: Dmnl
- RZ WC ratio - Units: Dmnl
- saturation water content - Units: Dmnl
- SAVEPER - Units: week
- scenescence trigger - Units: Dmnl
- scenescence trigger multiplier - Units: week
- season flag - Units: **undefined**
- season in - Units: **undefined**
- season out - Units: **undefined**
- seed - Units: $/acre

- seed fertilizers and chemicals - Units: $/acre
- Senescence GDD - Units: degree day
- senescence trigger accumulator - Units: Dmnl
- simulation start year - Units: year
- simulation year - Units: year
- simulation year LOOKUP - Units: Dmnl
- soil layers -
- soil layers AD - Units: mm
- Soil layers depletion - Units: mm
- soil layers FC - Units: mm
- soil layers PWP - Units: mm
- soil layers SAT - Units: mm
- soil layers TAW - Units: mm
- soil layers water content - Units: mm
- soil layers water content ratio - Units: Dmnl
- Soil profile depletion - Units: mm
- soil profile field capacity - Units: mm
- soil profile permenant wilting point - Units: mm
- Soil profile relative depletion - Units: Dmnl
- soil profile saturation - Units: mm
- Soil profile total depletion - Units: mm
- Soil Water Content - Units: mm
- Sowing depth Zini - Units: m
- Spill off - Units: m3/week
- Spill off water - Units: m3
- start of season flag - Units: Dmnl
- start of season stock - Units: **undefined**
- Start of yield and building up HI GDD - Units: degree day
- start season - Units: Dmnl
- start season flag LOOKUP - Units: Dmnl
- start year of construction - Units: year
- stock drain LOOKUP - Units: **undefined**
- Stomatal closure lower threshold depletion - Units: Dmnl

- Stomatal closure upper threshold depletion - Units: Dmnl
- Stomatal closure water stress coefficient Kssto - Units: Dmnl
- stomatal control shape factor - Units: Dmnl
- storage - Units: m3
- storage costs - Units: $/acre
- storage flag - Units: Dmnl
- storage flag LOOKUP - Units: Dmnl
- streamflow input - Units: m3/week
- streamflow LOOKUP - Units: Dmnl
- Streamflow rate - Units: m3/week
- sum of layers - Units: **undefined**
- SWC ratio - Units: Dmnl
- SWC rel - Units: Dmnl
- system capacity flow rate - Units: gpm/acre
- Target efficiency by target year - Units: Dmnl
- Tavg - Units: degreeC
- Tavg adjusted - Units: degreeC
- TAW of soil profile - Units: mm
- Tdiff - Units: degreeC
- technology rate after target year - Units: 1/year
- technology rate before target year - Units: 1/year
- Temperature adjustment lever - Units: degreeC
- Temperature biomass stress Ks - Units: Dmnl
- Temperature stress effect on biomass switch - Units: Dmnl
- thickness of soil layers - Units: mm
- Time at which yield starts - Units: week
- Time rate 2 - Units: 1
- TIME STEP - Units: week
- Time Stock for aging and senescence - Units: week
- Tmax adjusted - Units: degreeC
- Tmax lookup - Units: degreeC
- Tmin adjusted - Units: degreeC
- Tmin lookup - Units: degreeC

- ton to kg - Units: kg/t
- Total actual irrigation - Units: mm
- total area of each field - Units: ha
- total area of each field at the start of the season - Units: ha
- Total available water between upper and lower thresholds for canopy expansion -
- Units: mm
- Total available water between upper and lower thresholds for canopy senescence stress -
- Units: mm
- Total available water between upper and lower thresholds for stomotal closure -
- Units: mm
- Total expenses - Units: $/ha
- Total gross irrigation applied at farm gates - Units: m3
- Total gross irrigation applied at headworks - Units: m3
- Total gross irrigation water demand at farm gate - Units: m3
- Total gross irrigation water demand at headworks - Units: m3
- total live water storage - Units: m3
- Total Water Streamflow - Units: m3
- Total Water Supply - Units: m
- total water supply rate - Units: m3/week
- Total Water Withdrawal - Units: m3
- transpiration by layer - Units: mm/week
- Transpiration demand - Units: mm/week
- Transpiration rate - Units: mm/week
- trigger factor - Units: week
- trucking and marketing - Units: $/acre
- unit mm km to cubic meter - Units: m3/(mm*km2)
- Upper temperature - Units: degreeC
- utilities - Units: $/acre
- Water available to apply per irrigation event - Units: mm
- Water Conservation Objectives - Units: Dmnl
- water demand risk index - Units: Dmnl

- water demand risk score - Units: Dmnl
- Water economic index - Units: $/m3
- water horsepower required - Units: hp
- Water licence allocation - Units: m3
- water potential deficit - Units: m3
- Water Productivity Adjusted - Units: t/ha
- Water productivity index - Units: kg/m3
- Water Productivity WP - Units: gram/m2
- Water scarcity index - Units: Dmnl
- Water scarcity index 2 - Units: Dmnl
- Water shortage - Units: mm/ha
- water storage supply - Units: m3
- Water storage supply above deficit level - Units: mm
- Water supply major feedback ON OFF - Units: Dmnl
- water supply reliability LOOKUP - Units: Dmnl
- Weekly evapotranspiration rate - Units: mm/week
- Weekly Growing Degrees - Units: degree day
- weekly rain - Units: mm/week
- Weekly Rainfall - Units: mm/week
- Weekly Rainfall LOOKUP - Units: mm/week
- Weekly Reference Evapotranspiration - Units: mm/week
- WEI - Units: $/m3
- weight of access to incentives - Units: Dmnl
- weight of aridity index - Units: Dmnl
- weight of extension services - Units: Dmnl
- weight of relative productivity - Units: Dmnl
- weight of water demand risk - Units: Dmnl
- weighted average contribution margin per hectare - Units: $/ha
- weighted average field gross irrigation applied per hectare at farm gates - Units: m3/ha
- weighted average total crop yields per hectare - Units: t/ha
- weighted average total gross irrigation applied per hectare at headworks - Units: m3/ha

- weighting factor - Units: Dmnl
- Wind speed - Units: m/s
- Withdrawal - Units: m3
- WPI - Units: kg/m3
- WSI - Units: Dmnl
- WSI2 - Units: Dmnl

Appendix B: Supplementary Material for Chapter 2

B1 Summary

This document provides CropSD simulation results for maize production in Nebraska, USA, and potato production in Brussels, Belgium, and compares them to AquaCrop results for aboveground biomass and crop yield. As described in the main article, CropSD is a crop process model based on the FAO's AquaCrop model (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009).

The input data for each simulation set and the parameters used for each crop and soil type are described. CropSD was assessed using a range of irrigation treatments to cover allowable root zone water depletion from 20% to 100% of the root zone total available water (TAW).

The results for maize and potato production matched the results for barley presented in the article, and showed good agreement using weekly aggregated input data for both daily and semi-weekly simulation time steps; therefore, as explained in the main article, semi-weekly simulations provide a promising alternative to finer-resolution time steps. In contrast, weekly time step simulations produced the lowest agreement and highest uncertainty of the three time steps assessed.

B2 Maize production in Nebraska, USA

Simulations for maize production in Nebraska, USA, were conducted for 10 years (2001-2010) of weather data using both the daily AquaCrop model and the CropSD model for three simulation time steps. Climate data were obtained from the Champion weather station in Chase County, Nebraska, using the Automated Weather Data Network of the High Plains Regional Climate Center (High Plains Regional Climate Center, n.d.). Soil in the area is classified as loam soil with soil water contents at permanent wilting point, field capacity, and saturation of 0.135, 0.265, and 0.425 $m^3.m^{-3}$, and saturation hydraulic conductivity of 260 $mm.day^{-1}$ (Foster et al., 2015). Initial soil moisture conditions are assumed to be at field capacity. Note that simulation results for 2009 were omitted from the results, because of very low temperatures that did not permit sufficient growing degree days to accumulate during the irrigation season.

Foster et al. (2015) parameterized and validated AquaCrop for maize production in Nebraska and used the “conservative” (constant) crop parameters obtained from previous calibrations for maize production in a range of locations across the United States (Heng et al., 2009; Hsiao et al., 2009). Other local parameters were based on local crop conditions (Foster et al., 2015). We used the conservative crop parameters from Foster et al. (2015), as well as the following site-specific values:

Table B1. Summary of user specified and/or non-conservative maize crop parameters adjusted and calibration to local conditions in Nebraska

Parameter	**Value**	**Unit**
Planting date	May 1	
Planting density	74,132	plants.ha^{-1}
Time from planting to emergence	75	degree-day
Time from planting to flowering	850	degree-day
Time from planting to senescence (GDD)	1420	degree-day
Time from planting to maturity (GDD)	1670	degree-day
Maximum effective rooting depth (m)	1.7	m

Using the above model parameters, simulations were conducted for two alternative irrigation treatments based on allowable depletions of 20% and 100% of TAW. Figure S1 compares the AquaCrop-simulated aboveground biomass using daily weather data with the CropSD-simulated biomass using weekly aggregated weather data and the three simulation time steps: daily, semi-weekly, and weekly. Similarily, Figure B2 shows the simulated crop yields for the three simulation time steps.

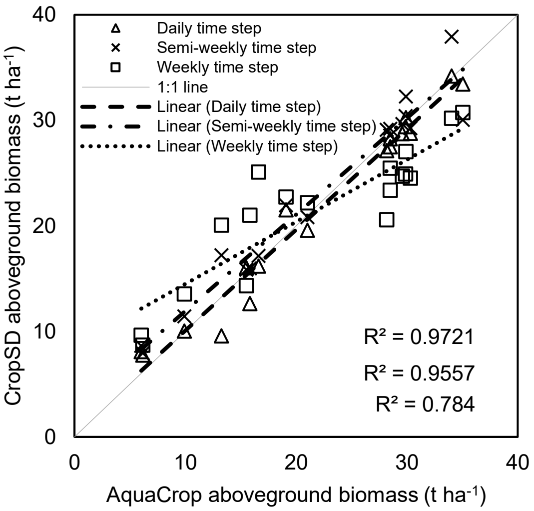


Figure B1. Results for CropSD versus AquaCrop in simulating the aboveground biomass for maize in Chase county in Nebraksa for the three simulation time steps evaluated in the study (i.e. daily, semi-weekly, and weekly)

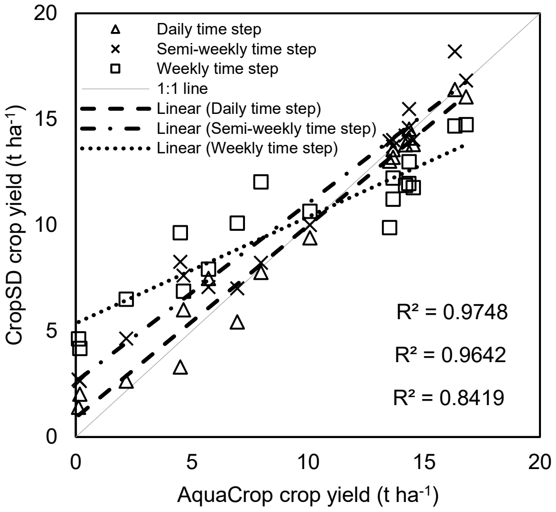


Figure B2. Results for CropSD versus AquaCrop in simulating the crop yield for maize in Chase county in Nebraksa for the three simulation time steps (i.e. daily, semi-weekly, and weekly)

B3 Potato production in Brussels, Belgium

Simulations for potato production in Brussels, Belgium, were also conducted for 10 years (1996-2005) of weather data using AquaCrop and three simulation time steps for CropSD. Daily climate data for Brussels are preloaded in AquaCrop for the years of 1979 to 2005; therefore, the default AquaCrop file was used to cover the simulated growing seasons and weekly-averaged values were used for CropSD. Soil in the area is classified as loamy with soil water contents at permanent wilting point, field capacity, and saturation of 0.15, 0.31, and 0.46 $m^3.m^{-3}$, respectively, and a saturation hydraulic conductivity of 500 $mm.day^{-1}$ for the first meter of the soil profile. Initial soil moisture conditions are assumed to be at field capacity at planting.

The default crop input files in AquaCrop, with conservative parameters unchanged, were used as crop inputs for CropSD, while the calibrated site-specific parameters were obtained from Foster et al. (2015). These values were used for both AquaCrop and CropSD are summarized in Table B2.

Table B2. Summary of user specified and/or non-conservative potato crop parameters adjusted and calibration to local conditions in Brussels, Belgium

Parameter	**Value**	**Unit**
Planting date	April 30	
Planting density	40,000	plants.ha^{-1}
Time from planting to emergence	95	degree-day
Time from planting to flowering	433	degree-day
Time from planting to senescence (GDD)	1325	degree-day
Time from planting to maturity (GDD)	1613	degree-day
Maximum effective rooting depth (m)	0.6	m

Simulations were conducted for two alternative irrigation treatments using allowable depletions of 20% and 100% of TAW. Figure B3 and Figure B4 compare the AquaCrop-simulated aboveground biomass and yield using daily weather data with the CropSD-simulated yields using weekly aggregated weather data and the three simulation time steps: daily, semi-weekly, and weekly, respectively.

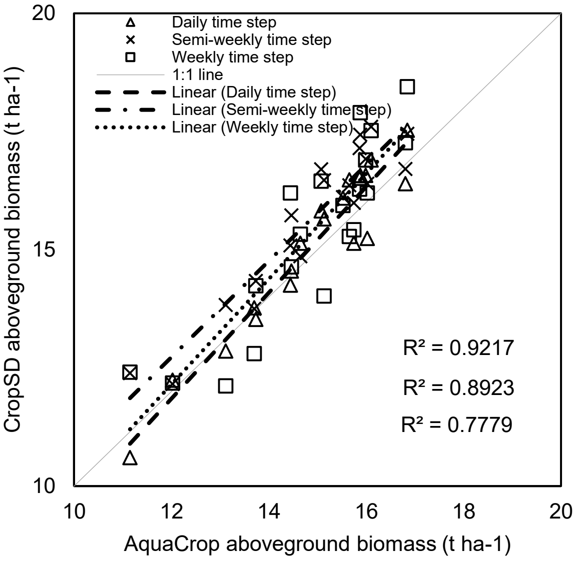


Figure B3. Results for CropSD versus AquaCrop in simulating the crop yield for potato crop in Brussels in Belgium for the three simulation time steps (i.e. daily, semi-weekly, and weekly)

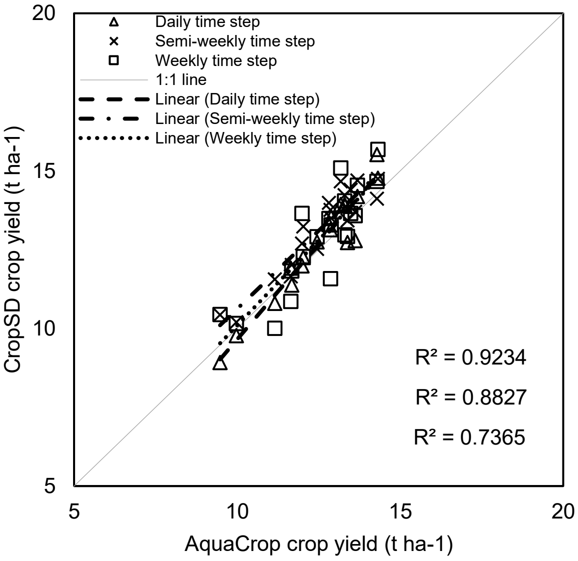


Figure B4. Results for CropSD versus AquaCrop in simulating the crop yield for potato crop in Brussels in Belgium for the three simulation time steps (i.e. daily, semi-weekly, and weekly)

B4 Model description

CropSD is based on the calculation procedures and algorithms of AquaCrop with adjustments to render it in a system dynamics format. For further information on AquaCrop, the reader is encouraged to refer to software publications (Hsiao et al., 2009; Steduto et al., 2009) and the reference manual (Raes et al., 2012).

System dynamics models, like CropSD, use stock-and-flow representations of physical processes. For example, a “stock” can represent the water storage in the soil profile and keep track of the incoming and outgoing water fluxes (“flows”, or water inputs to/outputs from the stock) at its boundaries. CropSD divides the soil profile into 15 layers (stocks) each with a thickness of 10 cm unless the root zone extends deeper, in which case the thickness of the last two layers are adjusted to cover the entire root zone. Infiltration and water redistribution (flows) in the soil profile after a wetting event – either irrigation or precipitation – are simulated using a modified tipping-bucket approach, where each soil layer fills to field capacity before water flows into the next layer and the drainage of excess water (above field capacity) is described by an exponential drainage function that takes into account the water content and the drainage characteristics of the soil layer (Raes et al., 2009), thus allowing water contents to be higher than field capacity. As described in the main text, this exponential function is not transferable to the semi-weekly and weekly time step configurations; therefore, in CropSD, excess water (above field capacity) drainage therefore occurs in a single time step for semi-weekly and weekly simulations, regardless of soil type. The model activates this second approach when it switches from a daily time step to the coarser simulation time steps.

Differences between CropSD and AquaCrop are minimal; all the necessary modifications are presented below (see also Table S3).

Table B3. Differences between AquaCrop and CropSD and the necessary modifications to allow implementation in coarse simulation time steps in a system dynamics framework.

Model component	AquaCrop	CropSD
Soil profile	Soil profile is divided into 12 compartments	Soil profile is divided into 15 compartments
Water redistribution and internal drainage	Described by an exponential drainage function based on a drainage coefficient (τ) derived from the saturated hydraulic conductivity	Same configuration as AquaCrop for daily time step simulation. For semi-weekly and weekly simulations, $\tau=1$, such that complete drainage occurs during one time step (maximum drainage)
Reference evapotranspiration	Based on FAO-56 Penman-Monteith equation (Allen et al., 1998b)	Choice of FAO-56 Penman-Monteith equation, three regression models by developed by Maulé et al. (2006), or Priestly-Taylor equation (Priestley and Taylor, 1972)
Root distribution	Distribution of 40, 30, 20, 10% are assigned to the upper, second, third and bottom quarter of the root zone	Following the CropSyst model, a linear decrease of root length occurs as a function of root depth, with a maximum at the top of the soil profile and a value of zero at the tip of the current root depth.
Climate input data format	Daily input data stored and adjusted through ASCII-formatted files	Weekly data stored in, and read from, an Excel spreadsheet

Reference evapotranspiration (ET_0) in CropSD is typically estimated using the FAO-56 Penman-Monteith equation (Allen et al., 1998b). To provide flexibility for longer simulated periods, four other temperature- and radiation-based methods with lower data requirements were included: three regression models by developed by Maulé et al. (2006), and the Priestly-Taylor equation (Priestley and Taylor, 1972). However, the analysis was based only on the FAO-56 Penman-Monteith equation as it is the only method used by AquaCrop.

AquaCrop describes crop phenology and the associated development of canopy cover and root depth as process variables, while CropSD uses state variables (stocks); this use of stocks also permits the model to carry the effects of management actions or climate conditions from one year to the next. As an example, the AquaCrop growing degree days (GDD) equations that describe canopy development and root depth were converted into rate equations through differentiation with respect to time. These differential GDD equations are then multiplied by the rate of change of GDD with respect to time, using the chain rule to represent the rates of change of the canopy cover growth and decline and root development. The resulting change in accumulated growing degree days per unit of time is given by:

$$\frac{\mathrm{dx}}{\mathrm{dt}} = \frac{\mathrm{dx}}{\mathrm{dGDD}} \cdot \frac{\mathrm{dGDD}}{\mathrm{dt}} \tag{B1}$$

where *x* is any crop development process, and *dGDD/dt* (°C/unit time) is referred to as the conversion coefficient, which represents the change in GDD in a single time step. For example, the canopy cover development rates – and similarly root depth development – are expressed in terms of growing degree days as follows:

$$\frac{\mathrm{dCC}}{\mathrm{dt}} = \frac{\mathrm{dCC}}{\mathrm{dGDD}} \cdot \frac{\mathrm{dGDD}}{\mathrm{dt}} \tag{B2}$$

$$\mathrm{CC} = \frac{\Delta\mathrm{GDD}}{\Delta\mathrm{t}} \int \frac{\mathrm{dCC}}{\mathrm{dGDD}} \mathrm{dt} \tag{B3}$$

B5 System Dynamics Framework

Of potential interest to the systems modeling community, CropSD is implemented in a system dynamics framework, which will permit SD modelers to replace the regression-based crop production functions currently used in agricultural production systems models (Kotir et al., 2016; Turner et al., 2016b) with a process-based crop model. Its use will allow systems modelers to 1) broaden their application domain into agricultural systems, 2) perform more accurate “long-run” integrated agricultural and water policy analysis, and 3) study the adaptive capacity of agricultural systems to climate change in the presence of coupled natural-human systems that often operate at different temporal scales. Moreover, the system dynamics modeling framework decreases simulation run times significantly and increases the capacity for detailed sensitivity runs and model calibration.

Appendix C: Supplementary Material for Chapter 3

Keywords used for the search of the different databases:

adaptation options; water
adaptation measures
adaptive management strategy; modeling
adaptive capacity; water policy
agent based; water policy
climate change adaptation; water
demand side water policy
econometric; water
integrated water resources management; water policy
modeling water policy
modeling adaptation
modeling water interventions
modeling policy analysis
modeling water strategy
modeling irrigation water policy
modeling residential water policy
modeling industrial water policy
modelling water policy
modelling water
multi-objective
optimization; water policy
optimization; water interventions
participatory modeling
policy measures
quantification water measures
quantify; water policy
regression analysis; water policy
simulating water policy
simulation; water adaptation
simulation; water policy
simulation; water policy options

supply side water policy
system dynamics; water policy
time series; water policy
water policy modeling
water policy
water interventions
water policy; artificial intelligence
water analysis; policy

Supplementary Table C1. Agricultural water management policy measures bibliography

Policy number	Studies count	References[1]
1-3	**3**	Alston, J.M., Chan-Kang, C., Marra, M.C., Pardey, P.G., Wyatt, T.J., 2000. A Meta-Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem? World. Alston, J.M., Pardey, P.G., 2001. Attribution and other problems in assessing the returns to agricultural R&D. Agric. Econ. 25, 141–152. doi:10.1016/S0169-5150(01)00072-X Evenson, R.E., 2001. Chapter 11 Economic impacts of agricultural research and extension, in: Handbook of Agricultural Economics. pp. 573–628. doi:10.1016/S1574-0072(01)10014-9
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Supplementary Table C2. Municipal water management policy measures bibliography

Policy number	**Study counts**	**Modelling approach**	**References**[1]
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	1	E/Panel data	Renwick, M.E., Archibald, S.O., 1998. Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? Land Econ. 74, 343. doi:10.2307/3147117
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	1	O/Two-stage optimization	Wilchfort, O., Lund, J.R., 1997. Shortage Management Modeling for Urban Water Supply Systems. J. Am. Water Resour. Assoc. 123, 250–258.
	1	Regression	Sovocool, K.A., Morgan, M., Bennett, D., 2006. An in-depth investiagation of Xeriscape as a water conservation measure. J. Am. Water Work. Assoc. 98, 82–93.
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9-15	**1**	S	Jacobs, H.E., Haarhoff, J., 2004. Application of a residential end-use model for estimating cold and hot water demand, wastewater flow and salinity. Water SA 30, 305–316. doi:10.4314/wsa.v30i3.5078
	1	E/Time-series intervention analysis	Shaw, D.T., Maidment, D.R., 1987. Intervention Analysis of Water Use Restrictions, Austin, TX. Water Resour. Bull. 23, 1037–1046. doi:10.1111/j.1752-1688.1987.tb00853.x
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		S/ABM	Kanta, L., Zechman, E., 2014. Complex Adaptive Systems Framework to Assess Supply-Side and Demand-Side Management for Urban Water Resources. J. Water Resour. Plan. Manag. 140, 75–85. doi:10.1061/(ASCE)WR.1943-5452.0000301.
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	1	S/ABM	Schwarz, N., Ernst, A., 2009. Agent-based modeling of the diffusion of environmental innovations - An empirical approach. Technol. Forecast. Soc. Change 76, 497–511. doi:10.1016/j.techfore.2008.03.024
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	1	O/Hybrid multiobjective algorithm	Creaco, E., Ph, D., Pezzinga, G., 2010. Multiobjective Optimization of Pipe Replacements and Control Valve Installations for Leakage Attenuation in Water Distribution Networks. water Resour. Plan. Manag. 141, 1–10. doi:10.1061/(ASCE)WR.1943-5452.0000458.
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	1	O/Two-stage optimization	Wilchfort, O., Lund, J.R., 1997. Shortage Management Modeling for Urban Water Supply Systems. J. Am. Water Resour. Assoc. 123, 250–258.
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	1	S/ABM	Schwarz, N., Ernst, A., 2009. Agent-based modeling of the diffusion of environmental innovations - An empirical approach. Technol. Forecast. Soc. Change 76, 497–511. doi:10.1016/j.techfore.2008.03.024
	1	S	Fewkes, A., 2000. Modelling the performance of rainwater collection systems: towards a generalised approach. Urban Water 1, 323–333. doi:10.1016/S1462-0758(00)00026-1
36	1	S/Mathematical Material Flow Analysis	Binks, A.N., Kenway, S.J., Lant, P.A., 2017. The effect of water demand management in showers on household energy use. J. Clean. Prod. 157, 177–189. doi:10.1016/j.jclepro.2017.04.128
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37	1	S/ABM	Chu, J., Wang, C., Chen, J., Wang, H., 2009. Agent-based residential water use behavior simulation and policy implications: A case-study in Beijing city. Water Resour. Manag. 23, 3267–3295. doi:10.1007/s11269-009-9433-2
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42	**1**	S/SD	Stave, K. a., 2003. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. J. Environ. Manage. 67, 303–313. doi:10.1016/S0301-4797(02)00205-0
	1	S/ABM	Galán, J.M., López-Paredes, A., Del Olmo Martínez, R., 2009. An agent-based model for domestic water management in Valladolid metropolitan area. Water Resour. Res. 45, 1–17. doi:10.1029/2007WR006536
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	2	E	Renwick, M.E., Archibald, S.O., 1998. Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? Land Econ. 74, 343. doi:10.2307/3147117

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	1	O/Two-stage stochastic optimization	Escriva-Bou, A., Lund, J.R., Pulido-Velazquez, M., 2015. Optimal residential water conservation strategies considering related energy in California. Water Resour. Res. 51, 4482–4498. doi:10.1002/2014WR016821
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46-49	**1**	E/Marshallian surplus	Grafton, R.Q., Ward, M.B., 2008. Prices versus rationing: Marshallian surplus and mandatory water restrictions. Econ. Rec. 84, 57–65. doi:10.1111/j.1475-4932.2008.00483.x
	1	E/Generalization method of moments	Garcia Valiñas, M. los A., 2006. Analysing rationing policies: drought and its effects on urban users' welfare (Analysing rationing policies during drought). Appl. Econ. 38, 955–965. doi:10.1080/00036840600638925
	1	E	Renwick, M.E., Archibald, S.O., 1998. Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? Land Econ. 74, 343. doi:10.2307/3147117
	1	S/SD	Wang, K., Davies, E.G.R., 2015. A water resources simulation gaming model for the Invitational Drought Tournament. J. Environ. Manage. 160, 167–183. doi:10.1016/j.jenvman.2015.06.007
	1	Discussion article	*Lund, J.R., Reed, R.U., 1995. Drought water rationing and transferable rations. J. Water Resour. Plan. Manag. 121, 429–437. doi:10.1061/(ASCE)0733-9496(1995)121:6(429)*
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	1	S/ABM	Kanta, L., Zechman, E., 2013. Complex Adaptive Systems Framework to Assess Supply-Side and Demand-Side Management for Urban Water Resources. J. Water Resour. Plan. Manag. 140, 75–85. doi:10.1061/(ASCE)WR.1943-5452.0000301.
53-54	**1**	Discussion article	*Byrnes, J., Crase, L., Dollery, B., 2006. Regulation versus pricing in urban water policy: The case of the Australian National Water Initiative. Aust. J. Agric. Resour. Econ. 50, 437–449. doi:10.1111/j.1467-8489.2006.00332.x*

2	S/ABM	Chu, J., Wang, C., Chen, J., Wang, H., 2009. Agent-based residential water use behavior simulation and policy implications: A case-study in Beijing city. Water Resour. Manag. 23, 3267–3295. doi:10.1007/s11269-009-9433-2 Koutiva, I., Makropoulos, C., 2016. Modelling domestic water demand: An agent based approach. Environ. Model. Softw. 79, 35–54. doi:10.1016/j.envsoft.2016.01.005

[1] *Non-quantitative studies are presented in italics*

S: Simulation;

O: Optimization;

E: Econometric/Regression-based;

SD: System Dynamics;

ABM: Agent Based Modelling

Supplementary Table C3. Industrial water management policy measures bibliography

Policy number	Study counts	Study type	References[1]
1-2	**1**	Review	*Harto, C.B., Yan, Y.E., Demissie, Y.K., Elcock, D., Tidwell, V.C., Hallett, K.C., Macknick, J., Wigmosta, M.S., Tesfa, T.K., 2011. Analysis of drought impacts on electricity production in the Western and Texas Interconnections of the United States. Argonne Natl. Lab. 161. doi:10.2172/1035461*
	1	Input-output tables	Gu, A., Teng, F., Wang, Y., 2014. China energy-water nexus: Assessing the water-saving synergy effects of energy-saving policies during the eleventh Five-year Plan. Energy Convers. Manag. 85, 630–637. doi:10.1016/j.enconman.2014.04.054
3	**1**	S	Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E.G.R., Zhou, Y., Clarke, L., Edmonds, J., 2015. Water demands for electricity generation in the U.S.: Modeling different scenarios for the water-energy nexus. Technol. Forecast. Soc. Change 94, 318–334. doi:10.1016/j.techfore.2014.11.004
4	**1**	S and O	Yu, F., Chen, J., Sun, F., Zeng, S., Wang, C., 2011. Trend of technology innovation in China's coal-fired electricity industry under resource and environmental constraints. Energy Policy 39, 1586–1599. doi:10.1016/j.enpol.2010.12.03
5	**1**	O	Zhang, X., Vesselinov, V. V., 2016. Energy-water nexus: Balancing the tradeoffs between two-level decision makers. Appl. Energy 183, 77–87. doi:10.1016/j.apenergy.2016.08.156
6	**1**	Review	*Harto, C.B., Yan, Y.E., Demissie, Y.K., Elcock, D., Tidwell, V.C., Hallett, K.C., Macknick, J., Wigmosta, M.S., Tesfa, T.K., 2011. Analysis of drought impacts on electricity production in the Western and Texas Interconnections of the United States. Argonne Natl. Lab. 161. doi:10.2172/1035461*
	1	O	Santhosh, A., Farid, A.M., Youcef-Toumi, K., 2014. The impact of storage facility capacity and ramping capabilities on the supply side economic dispatch of the energy-water nexus. Energy 66, 363–377. doi:10.1016/j.energy.2014.01.031
7-12	**2**	S	Lubega, W.N., Farid, A.M., 2014. Quantitative engineering systems modeling and analysis of the energy-water nexus. Appl. Energy 135, 142–157. doi:10.1016/j.apenergy.2014.07.101 Feeley, T.J., Skone, T.J., Stiegel, G.J., McNemar, A., Nemeth, M., Schimmoller, B., Murphy, J.T., Manfredo, L., 2008. Water: A critical resource in the thermoelectric power industry. Energy 33, 1–11. doi:10.1016/j.energy.2007.08.007
	1	Review	*Canadian Association of Petroleum Producers, 2011. Water Conservation, Efficiency and Productivity Plan - Upstream Oil and Gas Sector.*
13-19	**2**	S	Davies, E.G.R., Kyle, P., Edmonds, J.A., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv. Water Resour. 52, 296–313. doi:10.1016/j.advwatres.2012.11.020 Feeley, T.J., Skone, T.J., Stiegel, G.J., McNemar, A., Nemeth, M., Schimmoller, B., Murphy, J.T., Manfredo, L., 2008. Water: A critical resource in the thermoelectric power industry. Energy 33, 1–11. doi:10.1016/j.energy.2007.08.007
	1	O	Mughees, W., Al-Ahmad, M., 2015. Application of water pinch technology in minimization of water consumption at a refinery. Comput. Chem. Eng. 73, 34–42. doi:10.1016/j.compchemeng.2014.11.004
20	**3**	S	Byers, E.A., Hall, J.W., Amezaga, J.M., 2014. Electricity generation and cooling water use: UK pathways to 2050. Glob. Environ. Chang. 25, 16–30. doi:10.1016/j.gloenvcha.2014.01.005

			Koch, H., Vögele, S., 2009. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. Ecol. Econ. 68, 2031–2039. doi:10.1016/j.ecolecon.2009.02.015 Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E.G.R., Zhou, Y., Clarke, L., Edmonds, J., 2015. Water demands for electricity generation in the U.S.: Modeling different scenarios for the water-energy nexus. Technol. Forecast. Soc. Change 94, 318–334. doi:10.1016/j.techfore.2014.11.004
	1	S and O	Yu, F., Chen, J., Sun, F., Zeng, S., Wang, C., 2011. Trend of technology innovation in China's coal-fired electricity industry under resource and environmental constraints. Energy Policy 39, 1586–1599. doi:10.1016/j.enpol.2010.12.03
21-22	**2**	Review	*Canadian Association of Petroleum Producers, 2011. Water Conservation, Efficiency and Productivity Plan - Upstream Oil and Gas Sector.* *Harto, C.B., Yan, Y.E., Demissie, Y.K., Elcock, D., Tidwell, V.C., Hallett, K.C., Macknick, J., Wigmosta, M.S., Tesfa, T.K., 2011. Analysis of drought impacts on electricity production in the Western and Texas Interconnections of the United States. Argonne Natl. Lab. 161. doi:10.2172/1035461*
23-24	**1**	Review	*Canadian Association of Petroleum Producers, 2011. Water Conservation, Efficiency and Productivity Plan - Upstream Oil and Gas Sector.*
	1	S	Feeley, T.J., Skone, T.J., Stiegel, G.J., McNemar, A., Nemeth, M., Schimmoller, B., Murphy, J.T., Manfredo, L., 2008. Water: A critical resource in the thermoelectric power industry. Energy 33, 1–11. doi:10.1016/j.energy.2007.08.007
25-26	**2**	Input-output/ Computable general equilibrium model	Zhou, Y., Li, H., Wang, K., Bi, J., 2016. China's energy-water nexus: Spillover effects of energy and water policy. Glob. Environ. Chang. 40, 92–100. doi:10.1016/j.gloenvcha.2016.07.003 Rivers, N., Groves, S., 2013. The Welfare Impact of Self-supplied Water Pricing in Canada: A Computable General Equilibrium Assessment. Environ. Resour. Econ. 55, 419–445. doi:10.1007/s10640-013-9633-3
	1	S and O	Yu, F., Chen, J., Sun, F., Zeng, S., Wang, C., 2011. Trend of technology innovation in China's coal-fired electricity industry under resource and environmental constraints. Energy Policy 39, 1586–1599. doi:10.1016/j.enpol.2010.12.03
	2	E/Cross-sectional data	Dupont, D.P., Renzetti, S., 2001. The Role of Water in Manufacturing. Environ. Resour. Econ. 18, 411–432. doi:10.1023/A:1011117319932 Renzetti, S., Dupont, D.P., 1999. An assessment of the impact of charging for provincial water use permits. Can. Public Policy 25, 361–378. doi:10.2307/3551525
	1	E	Reynaud, A., 2003. An econometric estimation of industrial water demand in France. Environ. Resour. Econ. 25, 213–232. doi:10.1023/A:1023992322236
27-31	**1**	Review	*Canadian Association of Petroleum Producers, 2011. Water Conservation, Efficiency and Productivity Plan - Upstream Oil and Gas Sector.*

[1] *Non quantitative studies are presented in italics*

S: Simulation;

O: Optimization;

E: Econometric/Regression-based;

SD: System Dynamics;

ABM: Agent Based Modelling

Appendix D: Supplementary Material for Chapter 4

D1 Irrigation sector of southern Alberta

Alberta's irrigation sector has expanded considerably in the last two decades – see Figures D1, D2, and D3.

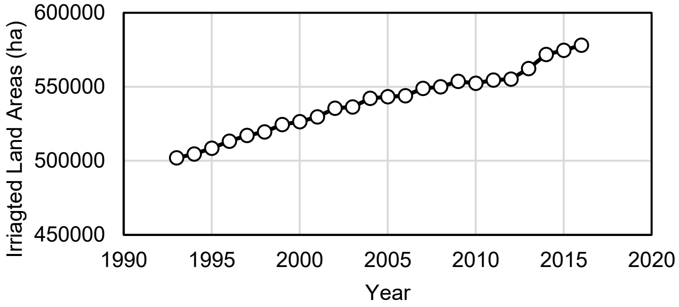


Figure D1. Irrigated land areas expansion in southern Alberta for the thirteen irrigation districts. Data source: AAF (2017)

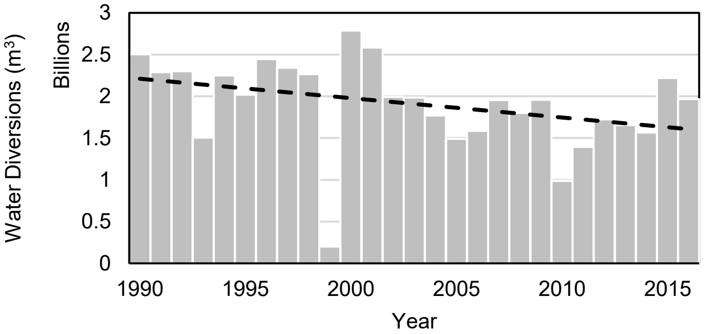


Figure D2. Total irrigation water diversions for the thirteen irrigation districts. Data source: AAF (2017)

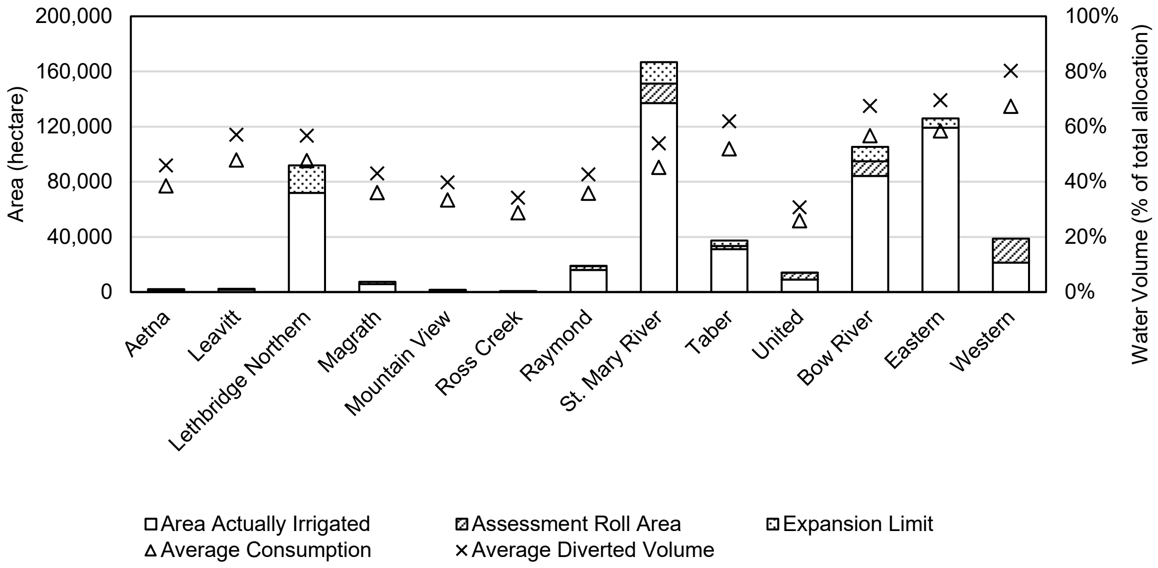


Figure D3. Current irrigated areas and expansion limits for the thirteen Irrigation Districts of Alberta. The figure also shows the percentage of the water diverted and consumed for the irrigated land areas average over the period 2005-2017. Data source: AAF (2017).

D2 AISS model components

D2.1 Process-based crop growth model component

The model simulates the dynamics of the soil water by dividing the soil profile into 15 equal layers (stocks), each with a thickness of 10 cm. Infiltration and water redistribution (flows) in the soil profile after a wetting event – either irrigation or precipitation – are simulated using a modified tipping-bucket approach, where each soil layer fills to field capacity before water flows into the next layer. Drainage of excess water (above field capacity) is described by an exponential drainage function that takes into account the water content and the drainage characteristics of the soil layer (Raes et al., 2009). The model uses thermal time, or growing degree days (GDD), as its default clock to express the different stages of the crop development (see supporting information in supplementary material for rendering the crop growth engine into system dynamics framework). Leaf development is expressed through the canopy ground cover, which is the fraction of the soil surface covered by the canopy. The canopy cover is then used as the basis of actual crop transpiration calculations. The model separates the non-productive soil evaporation from productive crop transpiration, and estimates crop yield by multiplying the biomass by a so-called harvest index (HI) (Raes et al., 2009; Steduto et al., 2012, 2009). The model derives the crop biomass from the amount of water transpired (Tr) by the crop using the water productivity parameter (WP) normalized for atmospheric evaporative demands ET_o and air CO_2 concentration, and is thus applicable to diverse locations and climate conditions, including future climatic changes (Raes et al., 2006). The difference in simulating the build-up of the harvest index makes the distinction between leafy vegetable crops, root/tuber crops, and fruit/grain producing crops. Further, to describe the relationships between actual crop yield and fertilizers application, the model uses the response functions developed by McKenzie et al. (2013, 2004) from field experiments for irrigated crops in Alberta.

To render AquaCrop in a system dynamics framework, the equations by AquaCrop that describe canopy development and root depth in terms of growing degree days (GDD) were converted into rate equations through differentiation with respect to time. These differential GDD equations are then multiplied by the rate of change of GDD with respect to time, using the chain rule to represent the rates of change of the canopy cover growth and decline and root development. The resulting change in accumulated growing degree days per unit of time is given by:

$$\frac{dx}{dt} = \frac{dx}{dGDD} \cdot \frac{dGDD}{dt} \tag{D1}$$

where x is any crop development process, and $dGDD/dt$ (°C/unit time) is referred to as the conversion coefficient, which represents the change in GDD in a single time step. For example, the canopy cover development rates – and similarly root depth development – are expressed in terms of growing degree days as follows:

$$\frac{dCC}{dt} = \frac{dCC}{dGDD} \cdot \frac{dGDD}{dt} \tag{D2}$$

$$CC = \frac{\Delta\mathrm{GDD}}{\Delta\mathrm{t}} \int \frac{dCC}{dGDD} dt \tag{D3}$$

Reference evapotranspiration (ET_0) is estimated using the FAO-56 Penman-Monteith equation (Allen et al., 1998a). Additionally, to provide flexibility for longer simulated periods and/or limited climate data, three other temperature- and radiation-based regression methods with lower data requirements developed by Maulé et al. (2006) were included.

The model estimates the crop yields of two groups of six distinct crops to represent a total of 12 fields of which six fields are irrigated and six are rainfed to allow for the calculation of the relative productivity and profitability between irrigated and rainfed agriculture and to represent a wide range of crop mix ratios. These crops are alfalfa, barley, canola, potatoes, sugar beets, and wheat and represent the majority of the crops growing in southern Alberta (AAF, 2017). These crops can be changed based on the case study as the availability of crop parameters.

D2.2 Water and temperature stresses component

Effects of soil water stresses on crop development are described using stress coefficients (Ks) following the same approach by AquaCrop, where Ks is a modifier of its target model parameter and varies from one (no stress) to zero (full stress) to indicate the relative intensity of the water stress effect. The stress indicator for soil water stress is the root zone depletion (the amount of water required in the root zone to reach field capacity) expressed as a fraction of the total available water for the crop to extract from the soil under a certain threshold (crop dependent). Three stress coefficients are included: canopy expansion stress, early canopy senescence, and stomatal closure.

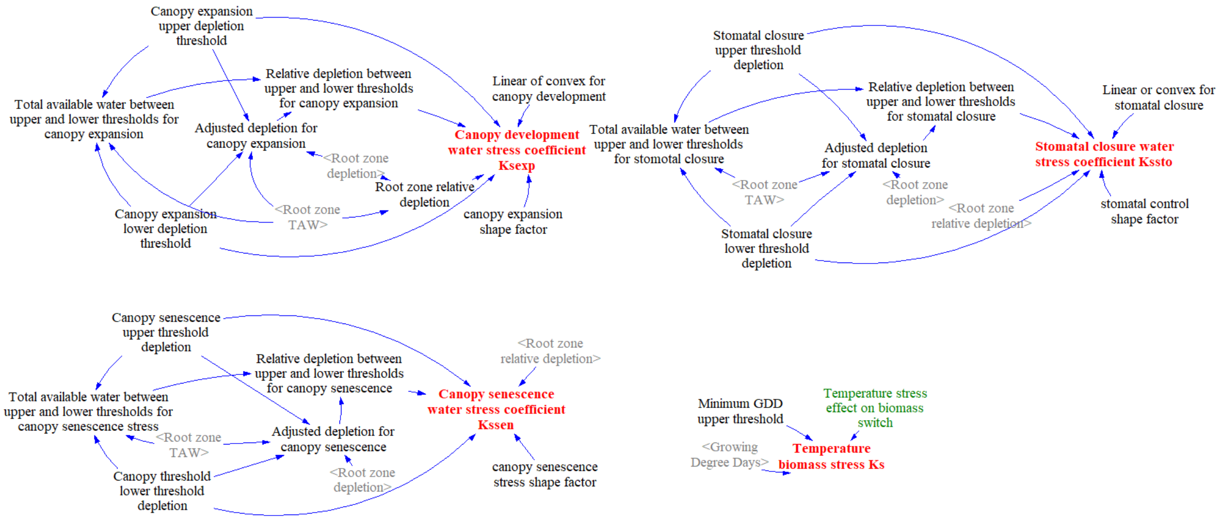


Figure D4. Crop growth water and temperature stresses component of AISS

Table D4. Soil water stress coefficients and their effects on crop growth

Coefficient	Effect
Canopy expansion Ks_{exp}	Reduces canopy expansion and might have a positive effect on the Harvest Index
Canopy senescence Ks_{sen}	Reduces green canopy cover and hence affects crop transpiration
Stomatal closure Ks_{sto}	Reduces crop transpiration and the root zone expansion, and (depending on timing and strength of the stress) might have a negative effect on the Harvest Index

D2.3 Water demand, supply, and management component

Under conditions of adequate supply, each field receives exactly what it requires, whereas if demands cannot be fully satisfied, a water shortage is generated, and an allocation scheme is implemented to release water with respect to the economic value of each field.

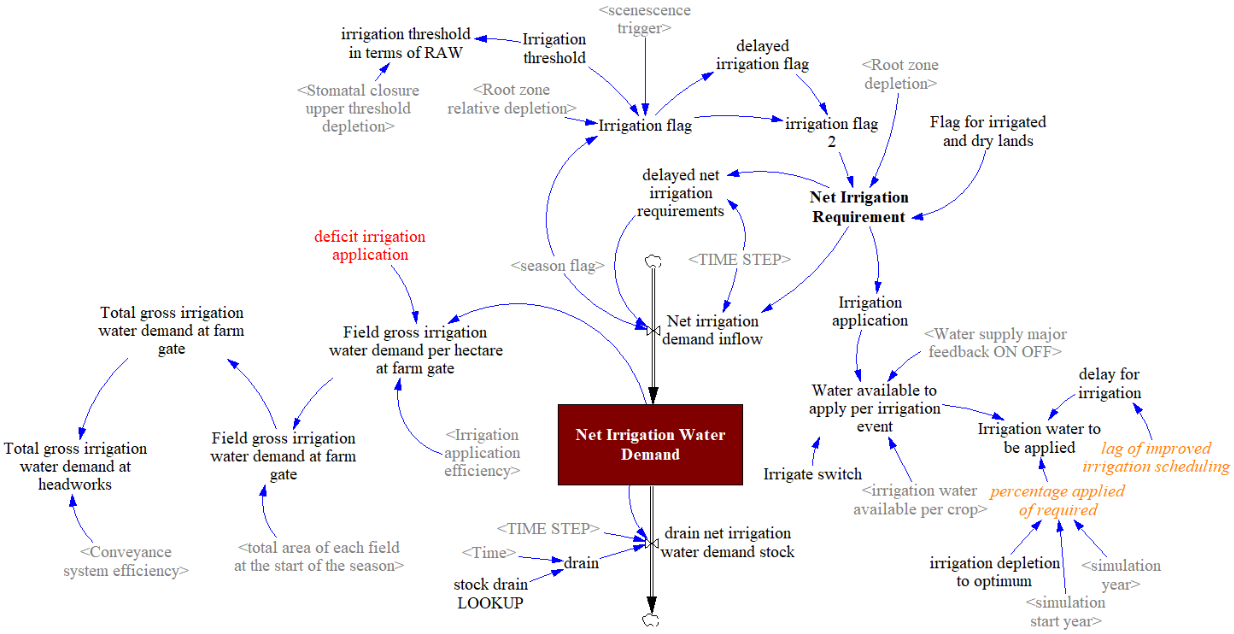


Figure D5. Crop water requirements and irrigation water demand component

The model calculates the on-farm irrigation water requirements based on the irrigation application efficiencies of four application methods namely, low pressure center pivots, high pressure center pivots, wheel move system, and gravity. Efficiency values were obtained from AAF (2016). Further, to account for future technologies that could emerge the model adds a fifth irrigation method under “new technology”. This serves as one of the variables that were introduced in the scenario analysis as discussed in section 4.5.1 for future simulations. Further, and based on the irrigation application technology, the model estimated the pumping hours for every irrigation event and thus allowing the quantify the changes in irrigation technology in terms of the cost of production as represented in section 4.4.2.4. Further, the model derives the total gross irrigation water demand at headworks from the on-farm requirement after accounting for the water loses from through the conveyance infrastructure from seepage and evaporation. The model incorporates three common conveyance systems namely, unrehabilitated earth canals, lined canals, and pipelines. Alberta has a total of 7,932 km of conveyance works of which about 3,900 km are in pipelines (AAF, 2017) and is planning to further reduce conveyance losses by replacing open channels to pipelines by 2035 to reach 5,925 km.

The change of the storage is represented as:

$$S(t) = \int_{t0}^{tn} [P(t) + INF(t) - E(t) - SP(t) - IRR(t)]dt + S(t_0) \qquad \text{(D4)}$$

where t is any time between t_0 and t_n ($t_0 \leq t \leq t_n$), S is storage, P is precipitation, INF is the instream inflows to the reservoirs, E is total evaporation, SP is the spill from the reservoir spillway, IRR is the total withdrawal by irrigation.

D2.4 Socioeconomic responses component

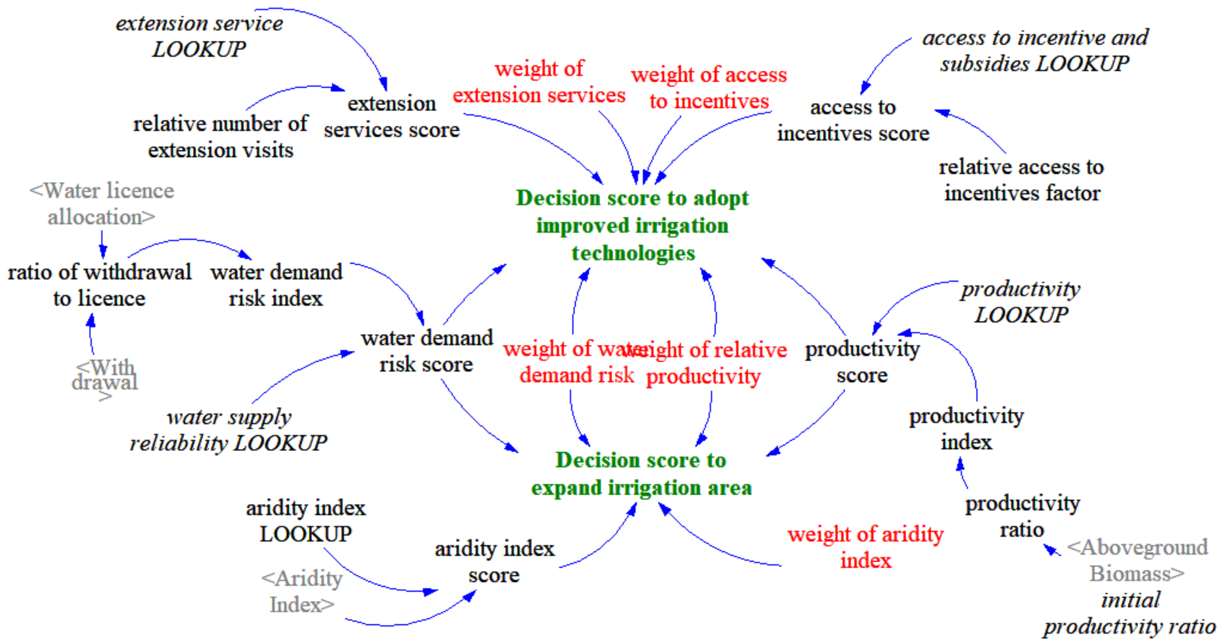
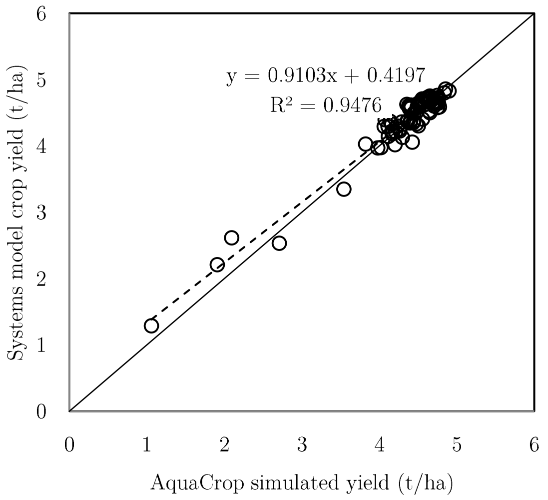


Figure D6. Socioeconomic model component. Equations and description of variables provided in Appendix A.

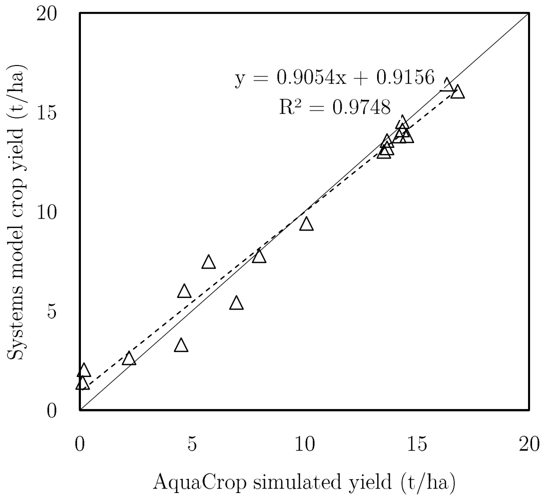
D3 Model validation

D3.1 Process-based crop growth component

(a) Barley in Alberta, CA



(b) Maize in Nebraska, US



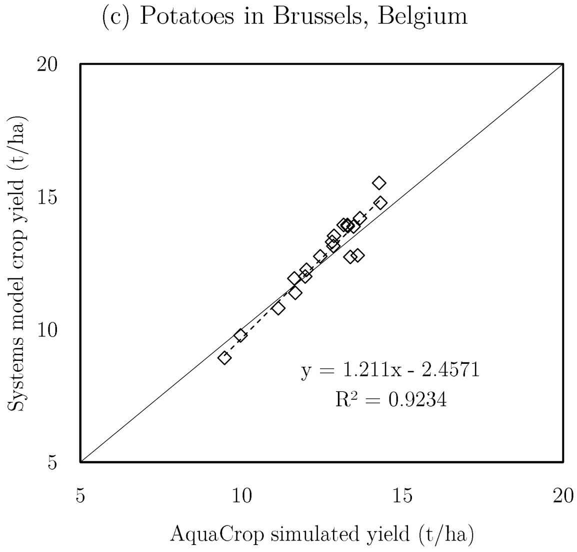

(c) Potatoes in Brussels, Belgium

Figure D7. Validation of the process-based crop growth component of AISS: (a) barley in Canada, (b) maize in Nebraska, and (c) potatoes in Belgium.

D3.2 Extreme conditions test results

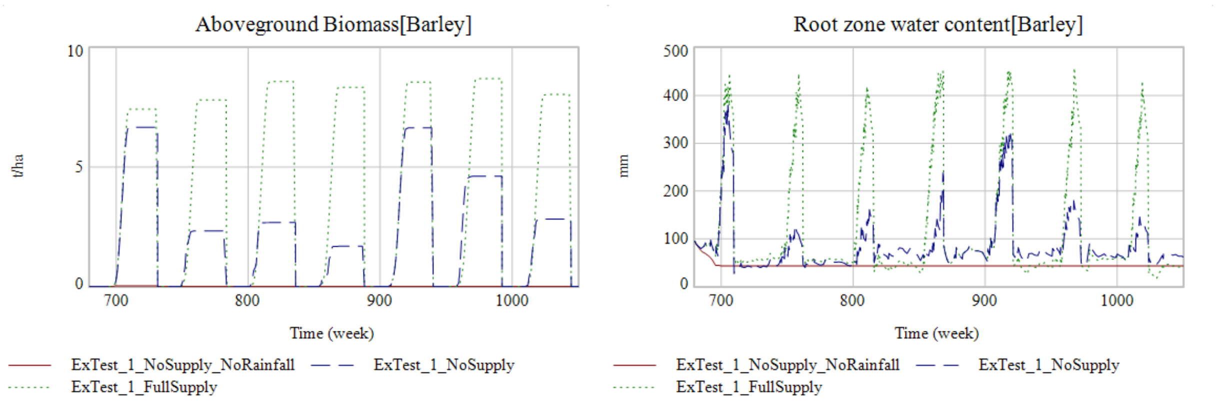


Figure D7. Extreme conditions test results for aboveground biomass and root zone water content

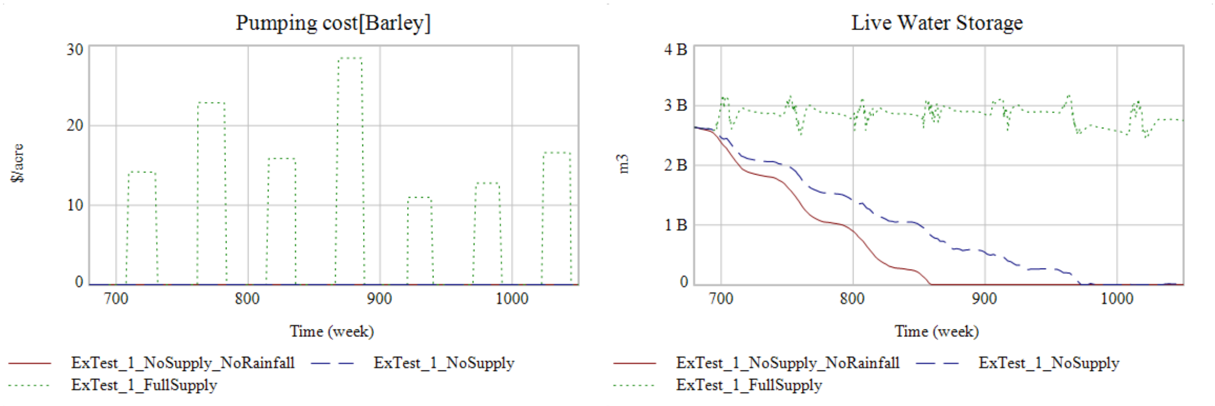


Figure D8. Extreme conditions test results for aboveground biomass and root zone water content

D4 Crop parameters inputs

Table D2. Crop parameters input for the six crops modeled using AISS

	Barley	Potato	Wheat	Canola	Sugar beet	Alfalfa
Sowing week since start of simulation year	18	18	18	18	18	18
Sowing week of the year	18	18	18	18	18	
Sowing to emergence or recovering	90	200	85	210	60	11
Sowing to maximum canopy	756	668	1100	750	649	500
Sowing to start senescence	925	984	620	975	1300	1500
Sowing to maturity	1350	1250	1100	1320	1411	1500
Sowing to start of yield, HI, flowering	810	550	620	660	1077	500
End of HI building up	1310	1167	1020	1046	1377	800
Length building up HI	500	617	400	386	300	800
Duration of flowering	150	160	140	210	0	0
Irrigation threshold	0.4	0.3	0.4	0.4	0.4	0.4
Crop type	2	1	2	2	1	3
Sowing to maximum rooting depth	756	1079	620	660	730	336
Base temperature	2	2	5	3	5	0
Upper temperature	28	26	35	29	30	30
Soil surface covered by an individual seedling at 90% emergence	1.5	15	1.5	5	1	1.8
Number of plants per hectare	3000000	60000	2700000	1000000	120000	160000
Canopy growth coefficient	0.008114	0.012615	0.010618	0.01163	0.015672	0.022071
Maximum Canopy Cover	0.8	0.92	0.95	0.9	0.98	0.87
Canopy decline coefficient	0.00571	0.002	0.007006	0.00274	0.022776	0.001842
Root Zone Development						
Minimum effective rooting depth	0.3	0.3	0.3	0.3	0.3	0.3
Maximum effective rooting depth	1.3	1.5	1.2	1.2	1	1.2
Sowing depth	0.3	0.3	0.3	0.3	0.3	0.3
Shape factor describing root zone expansion	1.5	1.5	1.5	1.5	1.5	1.5
Crop Transpiration						
Crop coefficient when canopy is complete but prior to senescence	1.1	1.1	1.1	1.1	1.1	1.05
Decline of crop coefficient (%/day) from ageing, nitrogen deficiency, etc.	1.05	1.05	1.05	1.05	1.05	1.05
Effect of canopy cover on reducing soil evaporation in late season stage	50	60	60	50	0	50
Biomass production and yield formation						
Water productivity normalized for ET0 and CO2	14	18	18	14	20	14
Reference harvest index	0.52	0.75	0.48	0.25	0.75	0.85
Initial harvest index	0.01	0.01	0.01	0.01	0.01	0.01
Growth coefficient HICG	0.013	0.012297	0.02	0.01575	0.028755	0.02074
Minimum growing degrees required for full biomass production	14	8	15	10	9	15
Coefficient of logistic function	0	0	0	0	0	0
Soil water depletion threshold for canopy expansion - Upper threshold	0.2	0.2	0.2	0.2	0.25	0.2
Soil water depletion threshold for canopy expansion - Lower threshold	0.65	0.6	0.65	0.55	0.7	0.7
Shape factor for Water stress coefficient for canopy expansion	3	3	4	3	4	3

Soil water depletion threshold for stomatal control - Upper threshold	0.6	0.55	0.55	0.6	0.65	0.55
Soil water depletion threshold for stomatal control - Lower threshold	1	1	1	1	1	1
Shape factor for Water stress coefficient for stomatal control	3	3	2.5	5	2.5	3
Soil water depletion threshold for canopy senescence - Upper threshold	0.55	0.7	0.7	0.7	0.75	0.55
Soil water depletion threshold for canopy senescence - Lower threshold	1	1	1	1	1	1
Shape factor for Water stress coefficient for canopy senescence	3	3	2.5	3	2.5	3
Soil water depletion threshold for failure of pollination - Upper threshold	0.85	0.8	0.8	0.85	1	0.85
Vol% at anaerobiotic point (with reference to saturation)	15	15	0	0	0	0
Maximum soil extraction rate	0	15	0	15	0	0
Maximum soil extraction term for the top 1/4 of soil	0	0.016	0	0.02	0	0
Maximum soil extraction term for the bottom 1/4 of soil	0	0.004	0	0.005	0	0

D5 Model Assumptions

AISS deals with the spatial variability through treating the different fields as arrayed compartments that describe homogenous subareas each with different crop type but similar key characteristics (e.g., soil properties, weather variability, or irrigation infrastructure improvements). Crop productions are then spatially aggregated to estimate the total production. The conceptualization of interactions of the different subsystems necessitate the choice of aggregation. Otherwise, integration across different spatial scales is not possible (Kelly et al., 2013). It is worth noting that few crop growth models have been used for regional analysis scaling up from field scale into landscape and regional scales conceptually through aggregating production (Hansen and Jones, 2000), or through linking existing crop models with geographical information systems (GIS) packages (Balkovič et al., 2013; Nichols et al., 2011) (see Ewert et al. (2011) and citations therein for a critical discussion on scaling).

Moreover, if the irrigation district expands or increases its expansion limit, it is assumed that each of the six fields increases by the same percentage. This method is a simplification of reality as the irrigation expansion depends on the availability of the land and its suitability for agriculture as well as its location relative to the irrigation infrastructure. This is one of the trade-offs of aggregation into larger units for simulation and for system dynamics which could potentially be addressed using spatiotemporal system dynamics approach by connecting the temporal model to a GIS database

It is assumed when running the model that the irrigators are optimal in their use of land, machinery, and time regarding sowing or transplanting and harvesting. More specifically, irrigators are assumed to irrigate shortly after an irrigation event is triggered, unless water shortage exists, otherwise the allocation routine is activated.

Moreover, the model assumes that the diffusion of the new irrigation application technologies is uniform across all irrigated land area. It was a necessity for upscaling the model application from the field scale to the basin scale for assessing the irrigation sector. A general limitation of system dynamics modeling is the limited treatment of space and spatial heterogeneity. AISS model could benefit from disaggregating of the different reservoirs for accurate evaporation area estimation and for incorporating individual reservoir operation rules. Therefore, spatiotemporal system dynamics may be worthwhile; however, they are complex to develop.

D6 Additional Model Results

Additional results for scenario group 6, for the rapid development scenarios, are shown in Table D3 and Figure D9.

Table D3. Percentage change for "rapid development" scenario group under different policy alternatives with unlimited and actual water supply simulated using the hydrologic model

Variable	Period	Scenario				
			Unlimited water supply		Ensemble model water supply	
		BC	RD_CM$_{\mathrm{WI}}$_85_PS$_{\mathrm{DC}}$	RD_CM$_{\mathrm{HV}}$_85_PS$_{\mathrm{HA}}$	RD_CM$_{\mathrm{WI}}$_85_PS$_{\mathrm{DC}}$	RD_CM$_{\mathrm{HV}}$_85_PS$_{\mathrm{HA}}$
Land productivity index						
	2016-2020	0	1.0	-0.6	1.0	-0.6
	2021-2025	0	3.5	-2.1	3.5	-2.1
	2026-2030	0	6.0	-3.5	6.0	-3.5
	2031-2035	0	8.7	-5.1	8.7	-5.1
	2036-2040*	0	**16.7**	0.4	**1.9**	0.4
Water economic index						
	2016-2020	0	0.7	4.4	0.7	4.4
	2021-2025	0	2.0	14.3	2.0	14.3
	2026-2030	0	1.4	29.3	1.4	29.3
	2031-2035	0	2.2	41.4	2.2	41.4
	2036-2040	0	**5.6**	50.8	**-1.6**	50.8
Land economic index						
	2016-2020	0	0.9	2.3	0.9	2.3
	2021-2025	0	2.8	7.7	2.8	7.7
	2026-2030	0	4.4	13.2	4.4	13.2
	2031-2035	0	5.9	17.4	5.9	17.4
	2036-2040	0	**13.3**	37.7	**-12.7**	37.7
Irrigation water withdrawal						
	2016-2020	0	1.4	-0.4	1.4	-0.4
	2021-2025	0	6.1	-1.3	6.1	-1.3
	2026-2030	0	11.6	-3.2	11.6	-3.2
	2031-2035	0	15.9	-5.2	15.9	-5.2
	2036-2040	0	**21.3**	5.2	**-2.6**	5.2

* bold text refers to estimation points affected by the feedback of the model

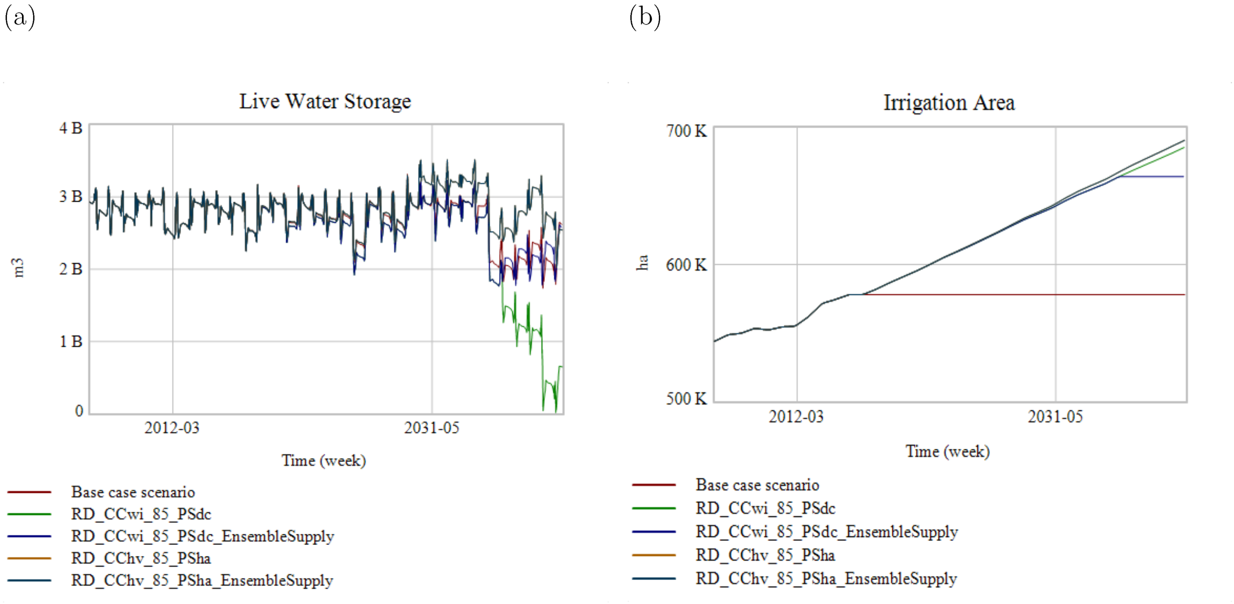


Figure D9. Simulated water storage (a) and irrigation area (b) for the “rapid development” scenarios in S6