University of Alberta

Meeting the *Water for Life* challenge: Management scenarios to improve irrigation water use efficiency and reduce water demand in the Western Irrigation District, Alberta

by

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To my Mother for her endless love and support

Abstract

Simulation of two alternative management scenarios - full rehabilitation and implementation of most efficient technologies, and water application restrictions - were investigated with the Irrigation Demand Model (IDM) as potential avenues to improve water use efficiency and reduce water demand in the Western Irrigation District (WID), Alberta. Results showed that the total district demand could decrease by up to 10% as a result of reduced on-farm and system losses. These improvements would not be sufficient to meet the goals of *Water for Life*. Simulation of water restriction applications showed that a limit of 6 inches/acre (502 mm/ha) would ensure adequate water supply for most crops, except alfalfa which would undergo yield reductions because of its high water requirements. The research demonstrated the strengths and limitations of existing models and investigated the use of CROPWAT for studying irrigated crops under reduced water supply in Alberta.

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Glossary

Actual evapotranspiration (ET_a): evapotranspiration under less than optimal condition (Doorenbos and Kassam, 1979).

Actual yield (Y_a): yield of a crop growing under conditions where the actual evapotranspiration is less than the maximum evapotranspiration (Doorenbos and Kassam, 1979).

Crop coefficient (K_c): a dimensionless multiplier applied to the reference evapotranspiration to obtain the actual evapotranspiration for a certain crop type (Allen *et al.*, 1998).

Crop coefficient curve: represents the changes in crop coefficient over the length of the growing season (Allen *et al.*, 1998).

Crop evapotranspiration (ET_c): evapotranspiration for a specific crop type for standard conditions (Allen *et al.*, 1998).

Crop growth/development stage: the growing period can be divided into four distinct growth stages: initial, crop development, mid-season and late season. The length of the crop growth stages depends on the crop type (Allen *et al.*, 1998).

Field water supply (FWS): total amount of water theoretically available to the plant to satisfy crop water requirements, defined as the sum of the available soil water in the root zone at planting and rainfall and applied irrigation depths over the growing season (Stewart and Hagan, 1973).

Maximum or potential evapotranspiration (ET_m): upper limit of evapotranspiration of a well-watered healthy plant under optimum growing conditions (Doorenbos and Kassam, 1979).

Maximum or potential Yield (Y_m): maximum yield of a crop growing under optimal conditions (Doorenbos and Kassam, 1979).

Reference evapotranspiration (ET_o): evapotranspiration for a hypothetical grass reference crop that is well watered (Allen *et al.*, 1998).

Return flow: volume of water that does not enter the soil after irrigation and returns to a downstream body of water as runoff or through the district's canal system.

Yield response factor (k_y): empirical coefficient that relates the ratio of actual to maximum yield and actual to maximum evapotranspiration (Doorenbos and Kassam, 1979).

1 Introduction

1.1 Global Importance of Irrigation

Irrigation is important to the global food supply. Irrigated agriculture provides approximately 40% of all crops and almost 60% of the cereal production from less than 20% of the total arable area (FAO, 2003).

Irrigation is expected to play an even greater role in meeting the food demands of a growing population increasing the pressure on existing water supplies. Irrigated land in the developing world is projected to expand by 40 million ha increasing the share of total crop production grown with irrigation to 47% in 2030 (FAO, 2003). Irrigation expansion will increase water use for agriculture, which already accounts for about 70% of the world's fresh water withdrawals (FAO, 2012a). In many parts of the world irrigation expansion is already reaching the point of diminishing returns and threatening ecosystem health making further irrigation development unfeasible (Postel, 1999).

Future investments in irrigation will be driven by several key factors: (1) the global need for more food, (2) a change in diets towards more water intensive food products, (3) the likelihood of smaller and less-secure water allocations for irrigation due to greater competition from other sectors, (4) the increasing importance of managing trade-offs between irrigation and ecosystem allocations, and (5) the changes in water supply and irrigation demand that are expected from climate change (Turral *et al.*, 2010). In particular, climate change may lead to a shift in optimal growing period and changes to cropping patterns, and is expected to increase global total water requirements, further limiting irrigation expansion (Döll, 2002). Moreover, the environmental, economic and social costs of large water projects are shifting the global focus towards improving water use productivity rather than escalating water supply (Gleick, 2003). Therefore, increasing productivity in irrigated agriculture will be a necessary approach to produce enough food with limited water supply and mitigate environmental problems (Ali and Talukder, 2008).

1.2 Irrigation in Alberta

In Alberta, irrigation is a major consumer of water, accounting for 71% of the surface water consumption in the province (Alberta Environment, 2002a). The majority of the irrigation activity occurs in the 13 irrigation districts in the South Saskatchewan River Basin (SSRB) located in the southern part of the province (Alberta Agriculture and Rural Development, 2000), as shown in Figure 1. Irrigation districts have a combined license allocation of 3.451 million dam^3 (Alberta Agriculture and Rural Development, 2011) which represents 43 % of the water allocations in the province (AMEC Earth & Environmental, 2007).

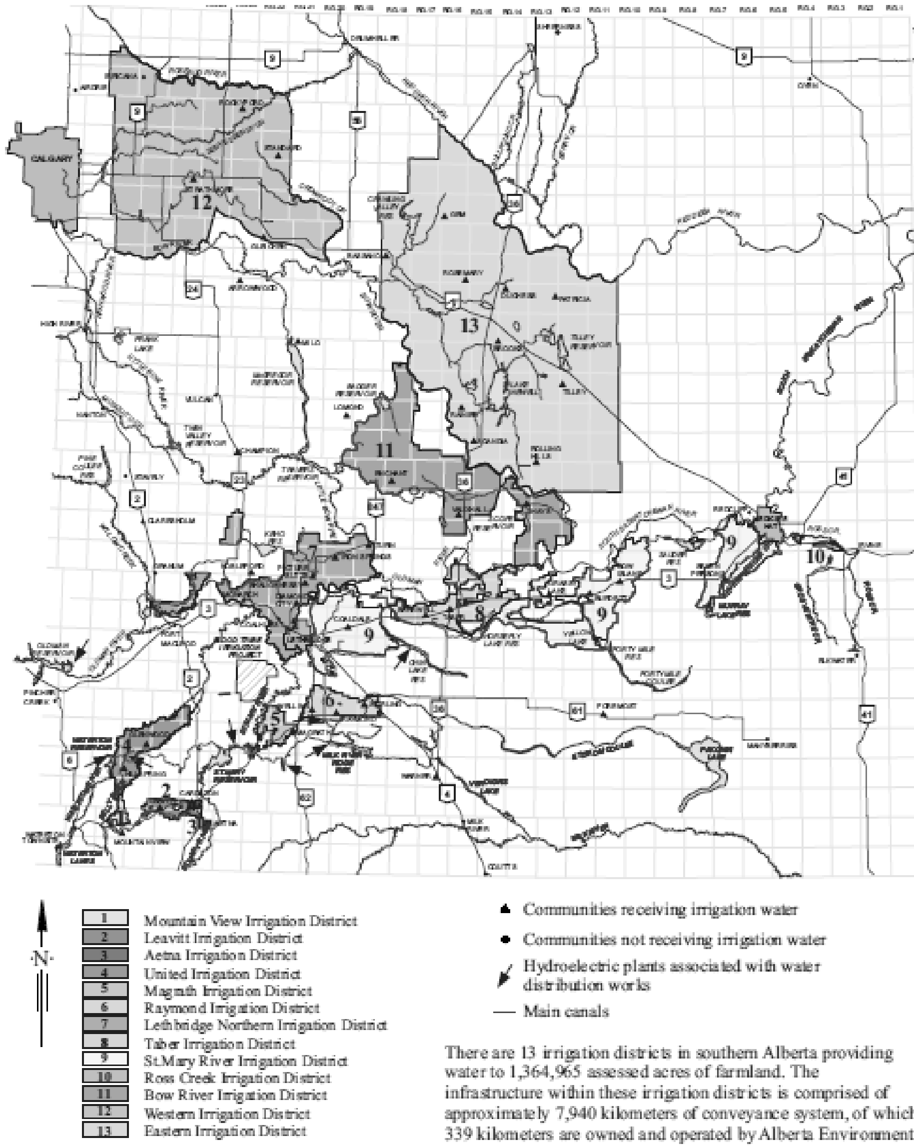


Figure 1 Alberta's Irrigation Districts (Alberta Agriculture and Rural Development, 2011)

Irrigation water is conveyed from the province's rivers to agricultural fields through a complex system of district-owned infrastructure and on-farm irrigation systems as illustrated in Figure 2 (Alberta Agriculture and Rural Development, 2000). Water may be stored in on-stream and off-stream reservoirs for controlled releases. Diversion structures direct water from a river or reservoir into earth and concrete canals. Water is then distributed through a system of main canals, and from these mains canals into lateral canals or pipelines. Check structures are used to raise the water level in a canal and facilitate the diversion of water. Farm turnouts are used to divert water from a canal into one or more pipelines. The pipelines, which are often located underground, bring water to one of several types of on-farm irrigation systems used to apply water to the crops. Finally, return flow channels, both natural and man-made canals, carry unused irrigation water back to a downstream river or stream.

In gravity systems, water is applied to a delivery ditch at the higher end of graded field using gated pipes, surge valves and siphon tubes to prevent erosion (Alberta Agriculture and Rural Development, 2000). Water flows in border dykes between rows of crops and is collected at the lower end of the field, where it may be pumped back for re-use or channeled to a return flow. Gravity systems are common in small farms where lower-value crops are irrigated. They are the least expensive to develop but have intensive labour requirements to operate.

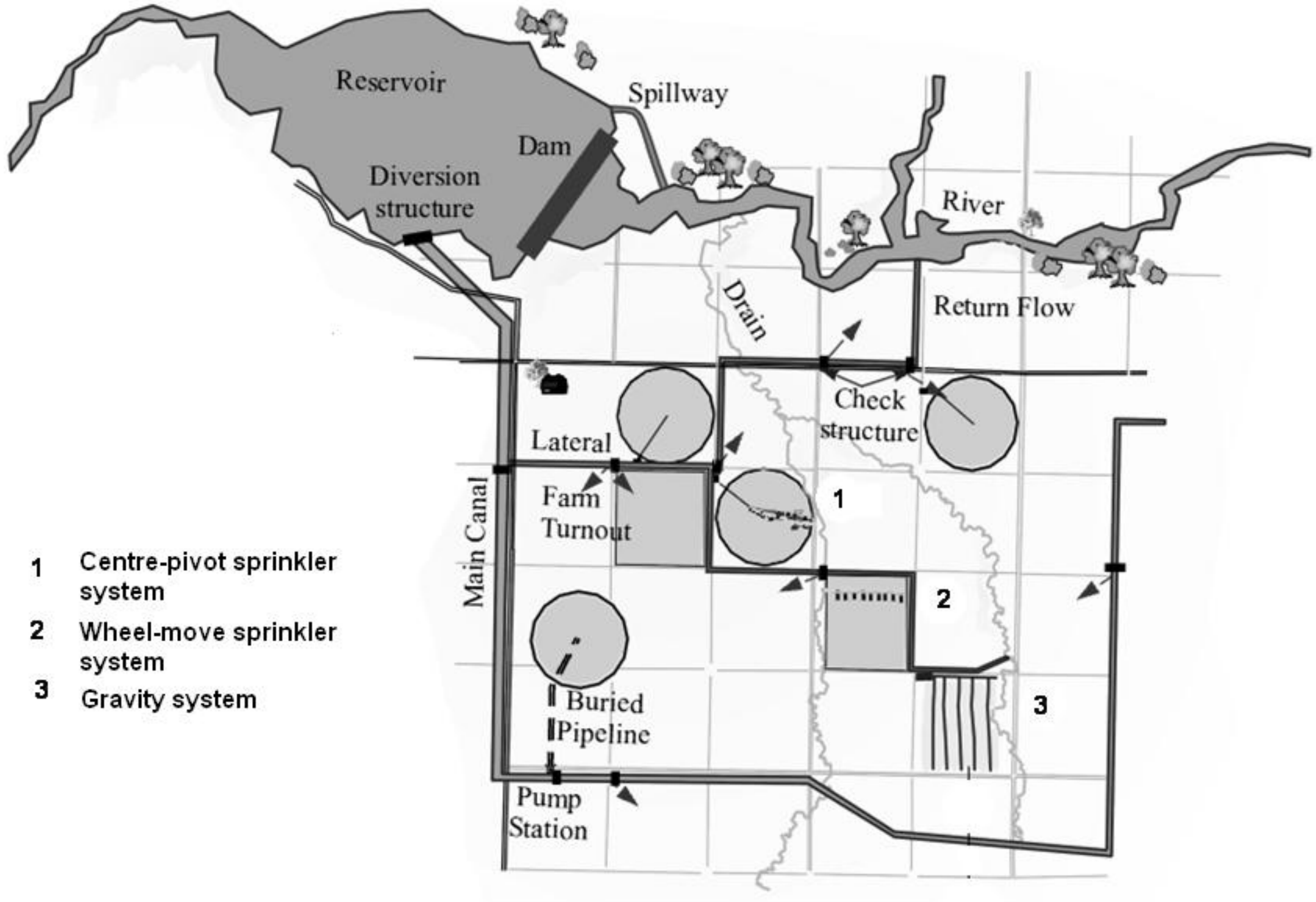


Figure 2 Alberta's Irrigation Infrastructure (adapted from Alberta Agriculture and Rural Development, 2000)

Sprinkler systems, including hand-move, wheel-move and centre pivot, are the most common types of irrigation systems in Alberta today (Alberta Agriculture and Rural Development, 2000). A sprinkler system is composed of a pump, a mainline or supply line pipe, lateral pipes and sprinkler heads. In hand-move systems, the laterals are laid out on the surface of an irrigated field and must be moved to cover various portions of the field requiring the system to be turned off temporarily. Similarly, in wheel-move systems, the lateral pipes are mounted on wheels that can be moved laterally across a field leading to short periods of system downtime. In centre-pivot sprinkler systems, the lateral pipes rotate on a mechanized swivel joint around the irrigated area. High pressure centre-pivot systems spray water high above the crop, leading to moderate evaporative losses, whereas low pressure systems have drop tube nozzles that spray water just above the crop, leading to lower evaporation losses and higher water application efficiencies (Irrigation Water Management Study Committee, 2002b).

Crops grown within the irrigation districts consist of forages including alfalfa, barley and corn silage, hay, and tame pasture; cereals like barley, wheat and oats; oil seeds such as canola and flax; and specialty crops like dry beans and peas, lawn turf, potatoes, and sugar beets (Alberta Agriculture and Rural Development, 2011).

Irrigation districts are important water management stakeholders in the province because they account for the greatest volume of water used and have the most senior rights (Alberta Economic Development Authority, 2008). Alberta's water management strategy, *Water for Life*, challenges irrigation districts to improve their water use efficiency and productivity by 30% from 2005 levels by 2015 (Alberta Environment, 2003; Government of Alberta, 2009). Achievement of this goal implies large water savings for the province. Furthermore, under the SSRB Water Management Plan, applications for new water licences in the Bow, Oldman and South Saskatchewan River Sub-basins are no longer being accepted (Alberta Environment, 2006). Therefore, irrigation districts play a key role in the ability to accommodate new users. Some irrigation districts have already engaged in water transfers with municipal water users and a few have amended their licenses to accommodate non-irrigation users.

Irrigation districts are actively working to improve their operations by rehabilitating their conveyance infrastructures, increasing the efficiency of the irrigation technology and promoting improved water management practices at the farm level. Increased water use efficiency, particularly from the implementation of more efficient irrigation technologies, has resulted in significant water savings which have allowed an increasing area to be irrigated with decreasing water diversions, as shown in Figure 3.

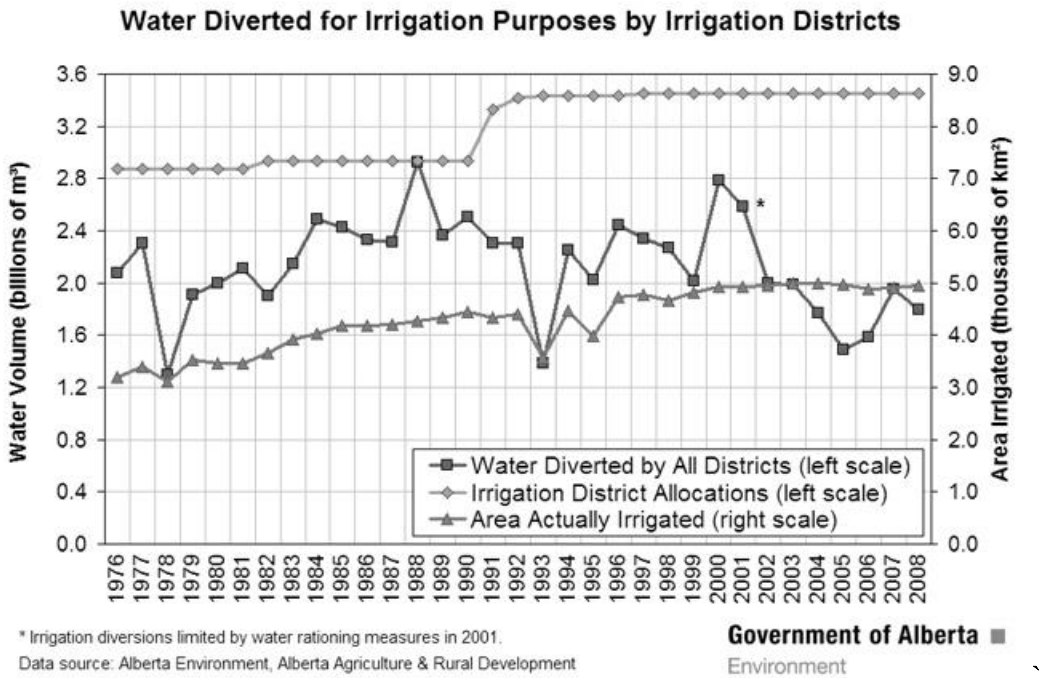


Figure 3 Water diversions by irrigation districts in Alberta

In the future, irrigated agriculture in Alberta is expected to play a greater role in meeting the global food demand through increased agri-food exports, and in fostering economic development for rural communities. In particular, food processing and exports of high quality traditional crops and specialty crops are expected to rise (Alberta Agriculture and Rural Development, 2000). The key industry sectors that have significant opportunities for growth in rural southern Alberta, particularly beef and pork, depend on continued water availability and competitive prices of irrigated annual forage and forage grains for feed (Alberta Agriculture and Rural Development, 2004). This increased water demand will require further irrigation expansion combined with improvements in irrigation efficiency and productivity to reduce effects on water supply.

1.3 Western Irrigation District

The Western Irrigation District (WID) is located east of Calgary in the Bow River basin and headquartered in Strathmore, Alberta – its conveyance system consists of a network of three main canals (A, B and C), each with a series of sub-canals and laterals, as shown in Figure 4. The WID is the most northern and western of all irrigation districts (Figure 1). Its proximity to Calgary and other rapidly growing urban centres makes it the most exposed of all districts to urban and industrial pressures.

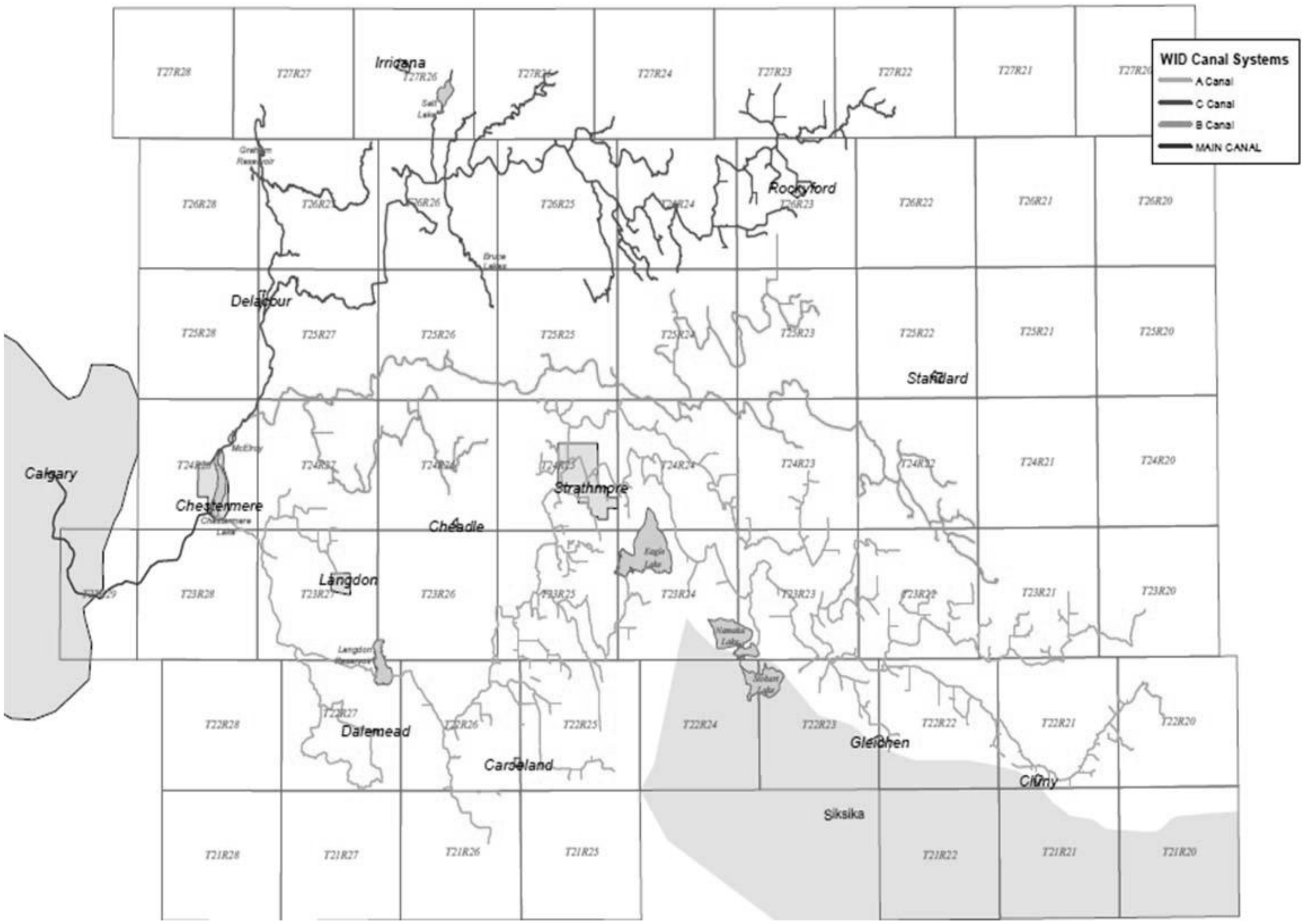


Figure 4 The WID canal network (Western Irrigation District, 2012)

The WID has a total “assessment roll area”, which is the maximum area of land that the district is allowed to irrigate, of 39,000 ha (95,000 acres). Its farmers irrigate annually approximately two-thirds of this area, using an average of 80% of the WID’s water licence allocation of 195,383 dam^3 (158,400 acre feet). To put this volume into perspective, the average annual natural discharge in the Bow River near the mouth is 3,950,494 dam^3 (Bow River Basin Council, 2005). The WID uses a high percentage of its licence allocation compared to other districts which divert 30 to 70% of their allocated water volumes (Alberta Agriculture and Rural Development, 2011). Water diversions in the WID vary annually depending on climatic conditions, area irrigated, crops grown, and irrigation efficiency. Figure 5 shows a decreasing trend in water diversions for the WID from the Bow River from 1976 to 2010. The area actually irrigated shows a variable, but increasing trend over the same period. Water use efficiency has grown: the district irrigated 15% more area in 2009 compared to 2005 with roughly the same amount of water. Figure 6 shows that the calculated cumulative, seasonal diversion volume in the WID has decreased over three recent time periods.

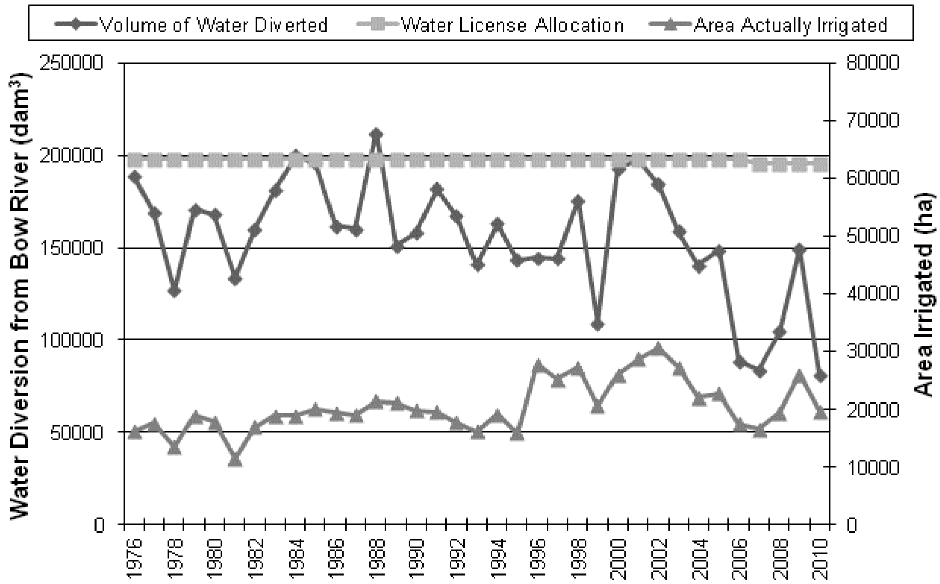


Figure 5 Water diversions for irrigation and actual area irrigated in the WID (Alberta Agriculture and Rural Development, 2011)

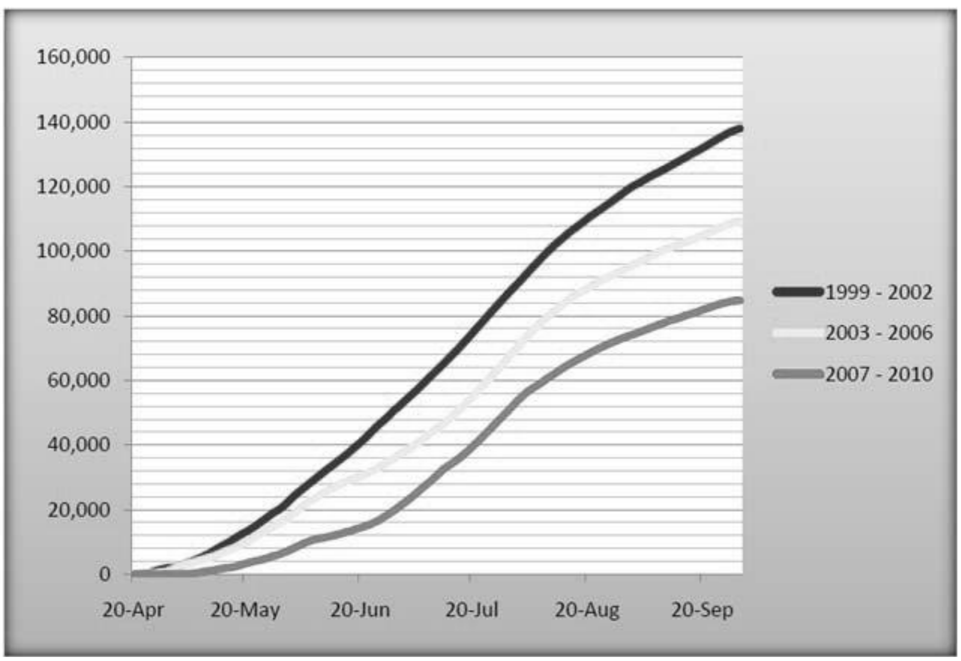


Figure 6 Cumulative diversion volume over the irrigation season for the WID for different recent time periods (personal communication Brian Sander)

Crops grown in the WID are largely forages (46%) and cereals (32%), with smaller percentages of oil seeds (17%) and specialty crops (5%), as shown in Figure 7 for 2009, a typical year used for later simulations. The crop mix in the WID is less varied than in other districts where the higher heat units allow for a larger number of crops to be grown, particularly specialty crops.

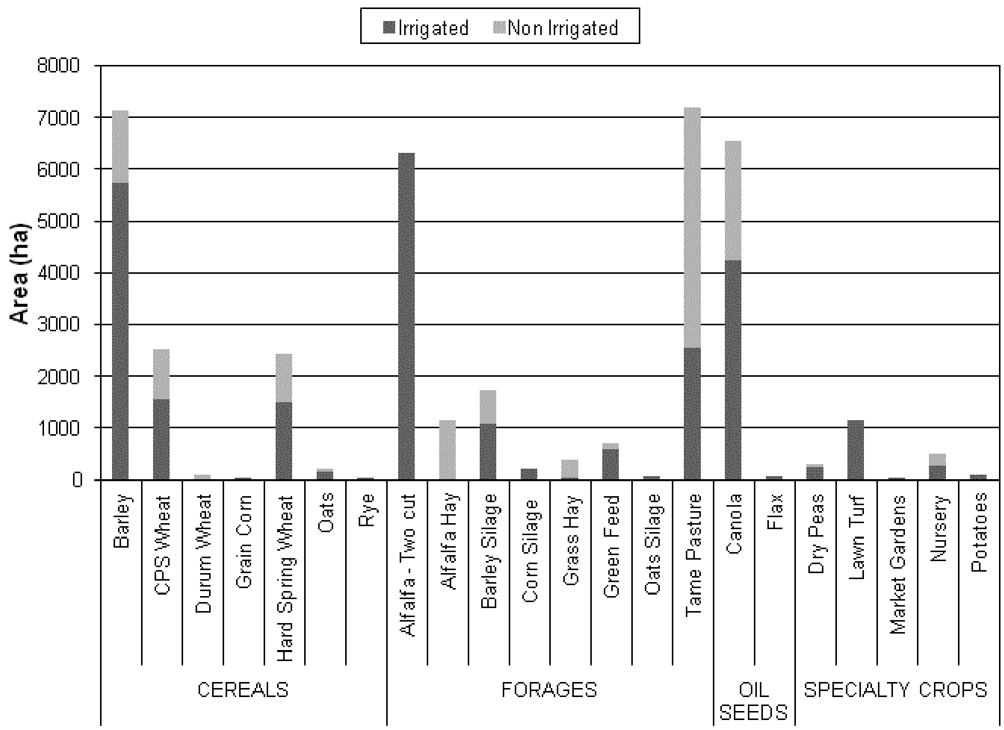


Figure 7 Crops grown in the WID in 2009 (Alberta Agriculture and Rural Development, 2010)

The district diverts its water from the "Western Headworks Weir" which lies downstream from Bearspaw Dam in the Bow River at Calgary. Water travels eastward through a system of 1938 km of conveyance and drainage works (Alberta Agriculture and Rural Development, 2011). Water distribution is performed by means of a continuous-flow system with a water-ordering component (Khan and Davies, 2011). Irrigators relay their demands to a ditch rider – or water district supervisor – forty-eight hours in advance and then the ditch rider plans delivery of water and ensures water orders are met. Khan and Davies (2011) provide a thorough overview of the WID's infrastructure and its operations.

The WID has two small reservoirs, Chestermere Lake and Langdon reservoir, with total surface water storage of 13075 dam^3 (Bow River Basin Council, 2005). This available storage volume is small compared to other districts. For example, the Bow River Irrigation District (BRID) and the Eastern Irrigation District (EID), which also divert water from the Bow River, control more than 80,000 and 650,000 dam^3 of storage, and the BRID has access to an additional 475,000 dam^3 of provincially-owned reservoirs (Alberta Agriculture and Rural Development, 2011). The lack of storage capacity in the WID increases the volume of water that needs to be diverted from the river because unused water must flow through the system and returned to the river. Complicating matters, Chestermere Lake is managed for recreational purposes, which further reduces the water available for irrigation since water levels are allowed to fluctuate by only 3 inches to accommodate a range of recreational activities (Khan and Davies, 2011). Finally, both reservoirs are located in the upstream part of the district reducing the flexibility of their operations because water requires a minimum of five to six days to travel from the Western Headworks weir to the end of the main canals. In summary, reservoir storage volume and location are major operational constraints for the WID.

The WID conveyance infrastructure has undergone less rehabilitation than other districts. In 2010, 63% of the WID's conveyance works were un-rehabilitated earth canals (Figure 8), compared to 7 to 25% in other districts (Alberta Agriculture and Rural Development, 2011). The remaining 37% of the conveyance infrastructure was composed of network segments that have undergone rehabilitation in recent years: newly installed open and closed pipelines (3 and 14%, respectively), rehabilitated earth canals (16%), membrane-lined canals (3%), and lined concrete canals (1%). The canal system in the WID is more than a century old so it requires rehabilitation, in addition to continuous maintenance, due to bank erosion, silt deposition, structural failure, and weed growth (Khan and Davies, 2011). The district's rehabilitation and maintenance efforts have included replacement of canals with buried PVC pipes; de-silting, reshaping and gravel-lining of main canals; installation of geo-membrane; and bank erosion and vegetation growth control (Khan and Davies, 2011). Rehabilitation projects have several advantages: reducing seepage and evaporation losses, improving conveyance system efficiency and water quality, reducing return flows, preventing structural failure, and increasing flow speed. The WID sees rehabilitation as the main way to save water. However, the district managers face two major challenges in putting future rehabilitation projects into practice: quantifying the potential water savings and addressing the high costs (Khan and Davies, 2011).

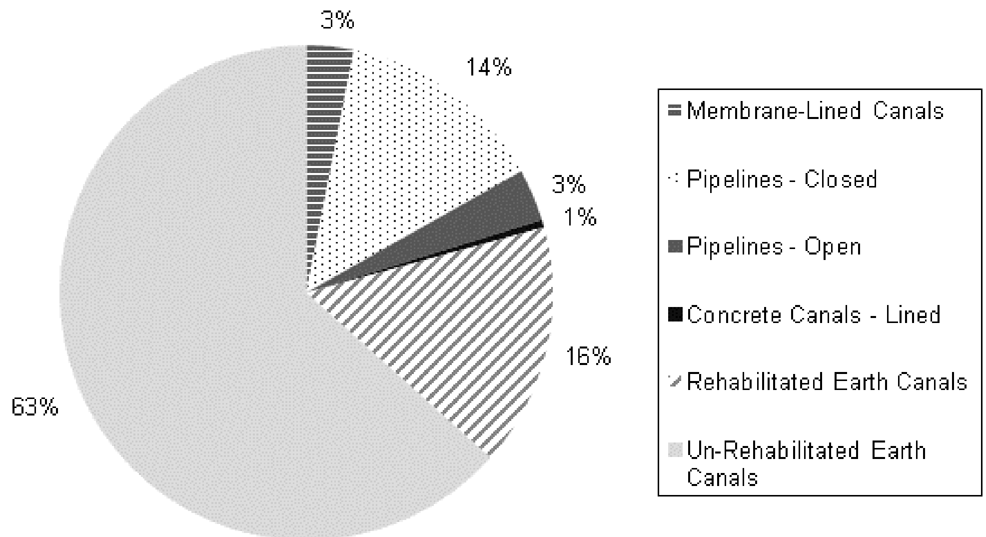


Figure 8 Conveyance infrastructure by type of works in 2010 in the WID (Alberta Agriculture and Rural Development, 2011)

At the farm level, irrigation is performed using high and low pressure pivot sprinklers (almost 70% of the area), wheel move, and gravity systems as seen in Figure 9. The efficiency of these systems ranges from 60 to 88% (Irrigation Water Management Study Committee, 2002b). Figure 9 shows a shift in on-farm irrigation method away from gravity systems towards more pivot sprinklers in the last decade as a result of the district's modernization efforts. The use of pivot sprinklers increased by 18% from 2000 to 2010; while the use of gravity systems decreased by the same amount. The significant drop in total irrigated area from

2008 to 2009 was largely attributed to the reduction in the area irrigated with gravity systems. This change in irrigation technologies represents substantial water savings because sprinkler systems are typically more water efficient than gravity systems.

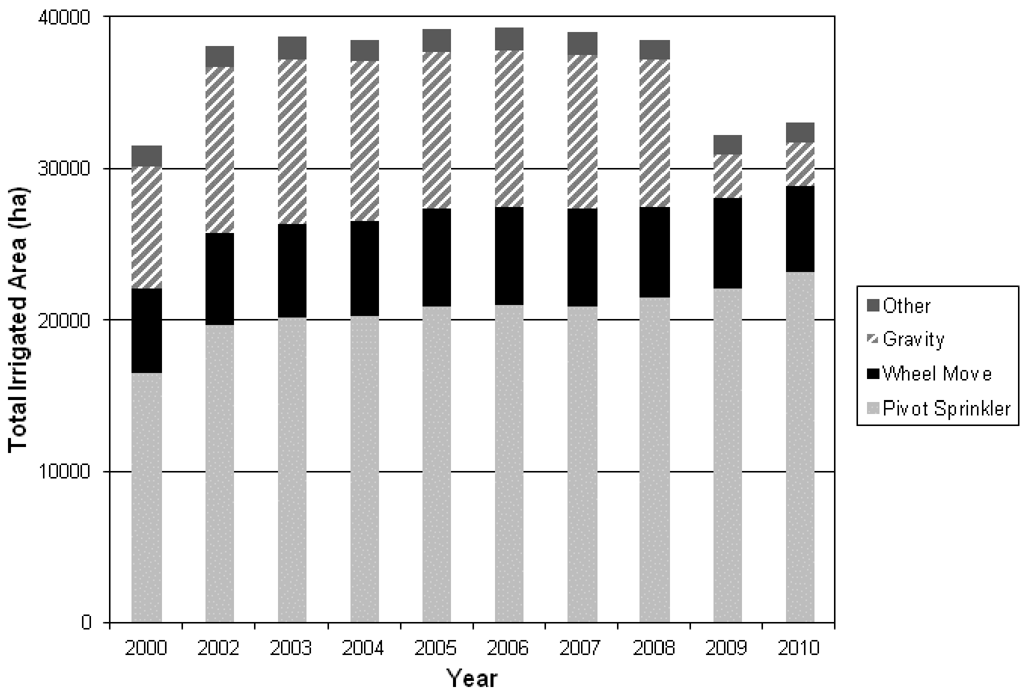


Figure 9 On-farm irrigation methods within the WID from 2000 to 2010 (Alberta Agriculture and Rural Development, 2011)

In summary, the WID faces significant challenges in improving its water use efficiency. Lack of reservoir storage and long travel times result in large water diversions because enough water needs to be kept in the conveyance system to meet downstream water demands. Moreover, a largely un-rehabilitated conveyance system leads to large system losses. So far the district has addressed the issue of irrigation efficiency from an engineering approach, through improvements to the physical and technical components of the irrigation system. In addition to further district modernization, this research explored alternative management options under a resource constrained scenario that would decrease water demand in the WID.

1.4 Study background

The research presented in this thesis was conducted as part of a larger study titled “Water: Making do with what we have”. The overall goal of the project was to inform the implementation of *Water for Life* in terms of agricultural water management. In particular, the objective of Part I: Water Management and Conveyance was to identify potential avenues for water savings in the Western Irrigation District.

The research built on the work of Khan and Davies (2011) who reviewed the physical and operational characteristics of the WID and identified six management policies and physical modifications to be investigated using Alberta Agriculture and Rural Development’s (ARD) Irrigation Demand Model (IDM). The options included:

1. full rehabilitation of WID infrastructure and implementation of most efficient irrigation technologies,

2. construction of a new “Bruce Lake” reservoir in the northwest of the WID, and of new check structures,
3. construction of efficiency dugouts throughout the district,
4. water application restrictions,
5. rotation scheduling, and
6. adjustment to advanced ordering time.

This thesis explores scenarios 1 and 4 - full rehabilitation and implementation of most efficient technologies and water application restrictions – as two potential avenues for water savings in the WID. The scenarios were selected based on the ability of existing modelling tools to perform the simulations and the interest expressed by WID and ARD managers. The scenarios address two different approaches to improve irrigation water use efficiency – supply and demand management – as described in Chapter 2.

1.5 Chapter Overview

The thesis is structured as follows. Chapter 2 reviews the concepts of crop water requirements, irrigation efficiency, water productivity, irrigation modernization, and deficit irrigation. This chapter also discusses tools to model irrigation water management, including the effects of water stress on crop yields. Chapter 3 describes the simulation methodology including a description of the Irrigation

Demand Model (IDM). A brief review of the use of CROPWAT for supplementary simulations of the water restriction scenario is also presented. Results of the simulation work are presented in Chapter 4 which also includes a discussion of the results and an analysis of their implications. Finally, conclusions and recommendations are presented in Chapter 5.

2 Literature Review

This chapter provides the theoretical context for the simulation work that follows. Reviewed are basic concepts and modelling approaches used in irrigation water management. Special attention is paid to research specific to southern Alberta. Key concepts include crop water requirements, irrigation efficiency, water productivity, irrigation modernization, and deficit irrigation.

Section 2.1 discusses briefly several concepts related to crop water requirements that form the basis of the modelling approaches discussed later.

Section 2.2 introduces the concepts of irrigation efficiency and water productivity, and describes irrigation modernization and deficit irrigation as ways to improve irrigation performance and water use at the farm and district levels. The two simulation scenarios explored in this research – full rehabilitation and implementation of most efficient technologies and water application restrictions – focused on these two approaches to improve the water use efficiency of the WID. Further, this section describes recent improvements in water use efficiency in Alberta and identifies potential avenues for improvement.

Section 2.3 reviews modelling tools that have been developed for irrigation water management. The models vary in purpose, scale, study area, and application. This section is meant to provide a context in which the strengths and weaknesses of the model used in this research, the Irrigation Demand Model (IDM) developed by Alberta Agriculture and Rural Development (ARD) and the Alberta Irrigation

Projects Association (AIPA), may be assessed. The IDM is described in detail in Chapter 3.

Lastly, Section 2.4 covers the methods used to model the effects of water stress on crop yields. Key topics include the characteristics of the relationship between crop yields and water use. Next is a review of different modelling tools that have been applied to develop optimal irrigation schedules for maximum yields and to study the consequences of water deficits on crop yields.

The chapter concludes with a brief summary of the key topics that will be useful in following chapters.

2.1 Crop Water Requirements

Water consumption by agricultural plants includes water evaporated and transpired from soil and plant surfaces (evapotranspiration) and a small percentage (less than 1%) retained in plant tissues (Jensen, 1968). The rate of evapotranspiration depends on climatic factors (solar radiation, air temperature, air humidity, and wind speed) and other physical factors (crop type and development stage, soil characteristics, amount of water available, and environmental aspects) (Allen *et al.*, 1998). Evapotranspiration for a reference crop (ET_o) – such as grass or alfalfa that have been widely studied – is usually calculated using one of several standard equations that estimate evapotranspiration from different climatic variables (for example, Jensen-Haise, Modified Penman and Priestley-Taylor). Federer *et al.* (1996) provide a detailed comparison of methods for calculating potential evapotranspiration, including the equations and parameters used in each. Out of these methods, the Food and Agriculture Organization of the United Nations (FAO) recommends the Penman-Monteith method as the sole ET_o method for calculating reference evapotranspiration because it provides actual crop water requirements that are consistent with data worldwide. The FAO method defines a hypothetical grass reference with crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23 (Allen *et al.*, 1998). The FAO Penman-Monteith method to estimate ET_o uses Equation 1

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \textbf{(1)}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

Crop evapotranspiration (ET_c) for a specific crop is then calculated from the reference evapotranspiration using Equation 2:

$$ET_c = K_c ET_o \quad \textbf{(2)}$$

where K_c is the crop coefficient, which integrates the effect of the main characteristics that distinguish a crop from the reference crop (crop height, albedo, canopy resistance, and evaporation from soil) (Allen *et al.*, 1998). The crop coefficient depends on crop type and climate, and it varies with crop growth stage as seen in Figure 10.

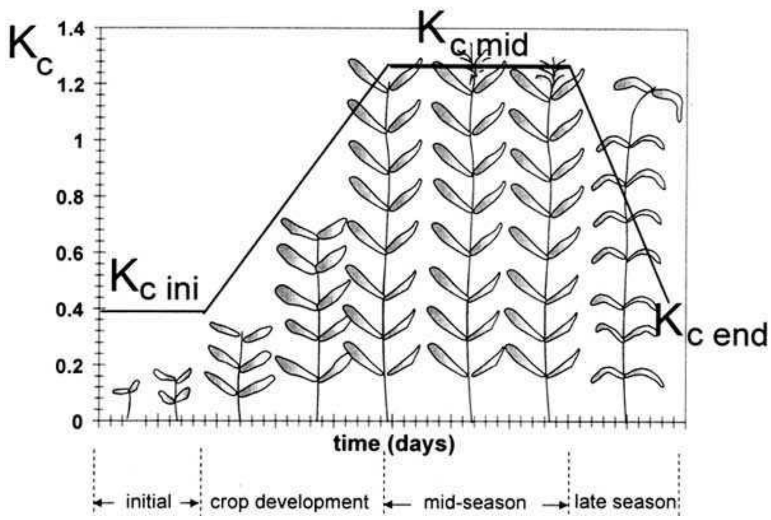


Figure 10 Generalized crop coefficient curve (Allen *et al.*, 1998)

Crop water requirements refer to the amount of water required to compensate for evapotranspiration losses in a cropped field. The total amount of water theoretically available to the plant to fulfill its water requirements, termed the field water supply (FWS), is the sum of the available soil water in the root zone at planting, and rainfall and applied irrigation depths over the growing season (Stewart and Hagan, 1973).

Two situations may develop when a crop is subjected to water stress – when water is supplied at rates below the crop water requirements. First, if enough soil water is available, the crop will extract water from the soil to compensate for the deficit and the practice will reduce irrigation water use as long as the soil water is replenished by seasonal rainfall (Fereres and Soriano, 2007). Second, if the soil water supply is inadequate, the water stress will result in less evapotranspiration as plants close their stomata, reduce their carbon assimilation and decrease their biomass production (Smith *et al.*, 2002). A reduction in biomass production and/or in the harvest index (the fraction of the biomass that is harvested) will lead to a reduction in yield (Fereres and Soriano, 2007). The maximum or potential evapotranspiration (ET_m) represents the upper limit of evapotranspiration from a well-watered healthy plant under optimum growing conditions. If crop water requirements are not fully met, the actual evapotranspiration (ET_a) will be less than ET_m. In addition to the crop type and species, the effect of water stress on growth depends on the timing and magnitude of the water deficit (Doorenbos and Kassam, 1979), as will be discussed in Section 2.4.

2.2 Improving Irrigation Efficiency and Water Productivity

2.2.1 Irrigation Efficiency

The concept of irrigation efficiency has been widely used to measure the performance of irrigation systems. Several definitions of irrigation efficiency exist and the fact that each incorporates different physical parameters can lead to misunderstandings.

In a seminal paper, Doorenbos and Kassam (1979) referred to irrigation efficiency as the volume of water stored in the root zone (m^3) as a percentage of the total water released at the project head works (m^3). Alternatively, they defined irrigation efficiency in terms of yield losses following the yield responses to water relationships. In this case, an increase in efficiency results in water saved that can be used to irrigate a larger area or to meet full crop requirements, both of which result in an increase in yields.

Burt *et al.* (1997) emphasized the importance of understanding where irrigation water ends up after an application, defining the physical boundaries of the area to be analyzed and identifying the time period for which the performance parameters are defined in order to make irrigation efficiency definitions clear and consistent. Additionally, they defined several irrigation performance measures that involve variables hard to quantify for most practical applications. Burt *et al.* (1997) stated that increasing irrigation efficiency does not necessarily increase water availability for other uses; water availability can only be increased by decreasing consumptive use.

Jensen (2007) summarized several definitions of irrigation efficiency and performance parameters and argued that traditional definitions of irrigation efficiency are useful for engineering design but can lead to misinterpretation when assessing the performance or productivity of an irrigation project. For example, the irrigation efficiency (Equation 3)

$$E_i = ET_i / (W_g - P_e) \tag{3}$$

represents the ratio of the water that was evaporated or consumed (ET_i) to the total water delivered (which is the gross supply of water delivered to a study area, W_g, minus the effective precipitation, P_e). The gross supply W_g is calculated as the sum of evapotranspiration, precipitation, surface runoff, change in water stored in the root zone, and percolation. The problem with this classical definition of efficiency is that the quantities in the definition are difficult and expensive to measure. A second problem is that the definition considers water that is diverted but not consumed to be a waste. Water that can be used elsewhere in the basin because it is returned should not be considered wasted as it can be used for other productive or beneficial uses downstream, as long as its quality is suitable. For river basin studies, the net or effective irrigation efficiency (Equation 4)

$$E_e = E_i + f_r(1 - E_i) \tag{4}$$

where f_r is the fraction of water diverted for irrigation that goes back to the river as return flow, might be a better performance indicator. The effective irrigation efficiency is thus a measure of how well water delivered was used for beneficial purposes, both intended and non-intended.

2.2.2 Water Productivity

The performance of an irrigation system may be more appropriately measured through terms that describe the physical and economic productivity of the system rather than in terms of efficiency (Jensen, 2007). For example, performance measures can involve water accounting and depletion concepts, productivity parameters that assess the economic output produced by the use of water, and benchmarking to track continual improvement. Wichelns (2002) described the importance of considering economic variables, such as externalities and opportunity costs, to ensure that improvements in irrigation water management result in economic efficiency. Wilchelns (2002) defined economic efficiency as a criterion that must be satisfied to ensure that limited resources are allocated and used to generate the maximum net benefits.

Water productivity is generally defined as the crop production per volume of water (Ali and Talukder, 2008). A related concept is “virtual water”, defined as the volume of water used in the production of a product (Hoekstra and Hung, 2005). Water productivity can be enhanced by agronomic, engineering and management improvements that increase the output per unit of water, reduce losses to unusable sinks, reduce water pollution, or reallocate water to higher priority uses (Ali and Talukder, 2008; Howell, 2001). An appropriate approach to enhance water productivity will be one that is suitable for the economic and social context and associates high water productivity with high or acceptable yields (Ali and Talukder, 2008). Molden *et al.* (2010) determined that improvements in water productivity are possible, particularly by increasing economic water productivity and adopting proven agronomic and water management practices. However, water savings are less likely to occur in areas that already exhibit high water productivity, in river basins where water is reused, or where producers do not have sufficient incentives to increase water productivity.

2.2.3 Irrigation Management Approaches

Improving irrigation performance under water scarcity requires policies and practices that can be grouped into two types of approaches: supply and demand management (Pereira *et al.*, 2002). Supply management policies, such as irrigation modernization, aim to increase the reliability and flexibility of water deliveries by increasing storage capacity, improving conveyance and distribution systems, reducing system losses, enhancing operation and maintenance, developing new sources of water supply, and improving on-farm practices to promote water conservation. Demand management policies focus on reducing irrigation requirements and adopting practices, such as deficit irrigation, that increase yields and income per unit of water used. The two simulation scenarios explored in this research – full rehabilitation and implementation of most efficient technologies, and water application restrictions – address supply and demand management approaches, respectively. The advantages and disadvantages of irrigation modernization and deficit irrigation are described next.

I. Irrigation Modernization

Modernization and optimization of irrigation systems can contribute to increased water productivity (Playán and Mateos, 2006). Irrigation modernization includes changes to physical structures, equipment and technologies, as well as changes to the management and institutional frameworks, water delivery services and farmers' irrigation scheduling (Playán and Mateos, 2006). Figure 11 summarizes the expected outputs of irrigation modernization and optimization.

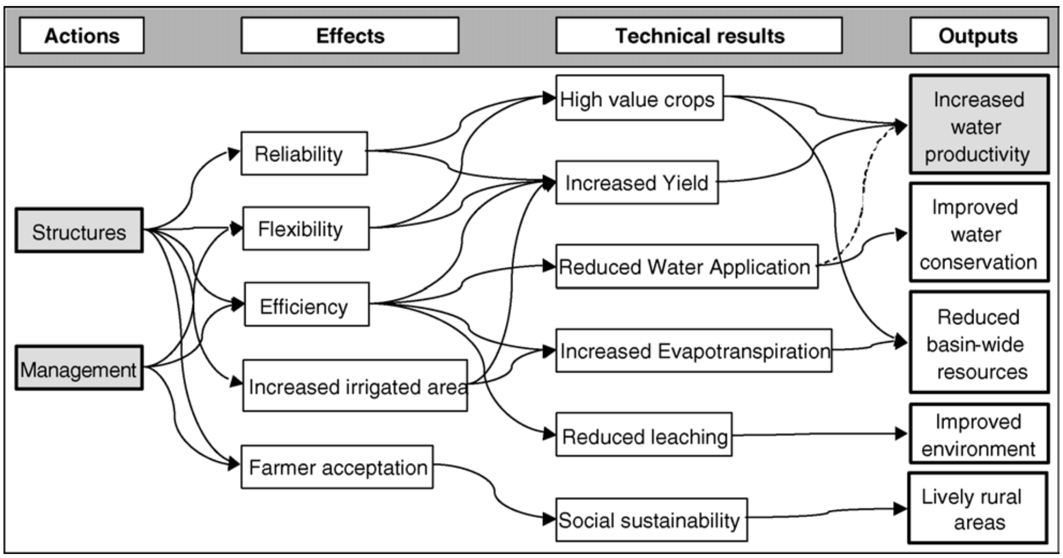


Figure 11 Flux diagram of the actions, effects, technical results and outputs related to irrigation modernization and optimization (Playán and Mateos, 2006)

At the district level, the goal of modernization is to improve the reliability, flexibility and efficiency of water deliveries; this goal is usually achieved by upgrading the irrigation structures or implementing changes to management practices (Playán and Mateos, 2006). For example, Lecina *et al.* (2005)

determined that irrigation efficiency could be improved in the Irrigation District V (five) of Bardenas, Spain by reducing the irrigation intervals, which in turn would reduce the irrigation depth that farmers tended to apply to ensure adequate water in the soil between applications. At the farm-level, higher irrigation performance, namely water application uniformity and efficiency, can be achieved through combined improvements in irrigation methods and scheduling which can involve water balance simulation models, monitoring the soil moisture or a combination of both (Playán and Mateos, 2006; Pereira, 1999). For instance, in the Loma de Quinto Irrigation District in Zaragoza, Spain, the technical deficiencies of the irrigation systems – such as the design and operating conditions of the sprinkler systems – and inadequate irrigation scheduling that resulted in water stress and yield reductions, were identified as major causes for low water use efficiency in the district (Dechmi *et al.*, 2003a; Dechmi *et al.*, 2003b).

Irrigation modernization involves changes in water use practices that can have implications for water conservation at the basin scale. In particular, irrigation modernization can lead to reduced water availability from increased crop production and decreased irrigation return flows for downstream users (Lecina *et al.*, 2010).

Future investments in irrigation modernization should be aimed at ensuring sustainability by minimizing consumptive water use in regions of water scarcity or economic competition for water, and maximizing productivity without worsening ecosystem degradation (Turral *et al.*, 2010).

II. Deficit Irrigation

Given the connection between water, ET and yield, deficit irrigation has been investigated extensively as a strategy to maximize water productivity in dry regions and where water supplies are limited (Fereres and Soriano, 2007; FAO, 2002; Geerts and Raes, 2009). Deficit irrigation involves the application of less water than a crop typically requires for maximum yield (Fereres and Soriano, 2007). The objective of deficit irrigation is to save water by limiting irrigation applications to the most water-sensitive growth stages or by eliminating irrigation events that have little impact on yield and thus minimal overall effects on the crop (Geerts and Raes, 2009; Kirda, 2002). Water applications are therefore restricted to water-sensitive stages, typically emergence, flowering and early yield formation, depending on the type of crop (Doorenbos and Kassam, 1979; Geerts and Raes, 2009).

Observations of yields under deficit irrigation show that yields for certain crops are reduced under limited water supply. For example, alfalfa yields under midsummer deficit irrigation (no irrigation in July and August) decreased by 4.68-6.47 Mg/ha compared to fully irrigated alfalfa in California (Hanson *et al.*, 2007). A study of wheat in Bangladesh concluded that grain yield reductions were greatest when the deficit occurred in early growth stages (Ali *et al.*, 2007). Ali *et al.* (2007) found that deficit irrigation in alternate stages (alternate drying and re-watering during crown root initiation, jointing to shooting, booting to heading, and flowering to soft dough) may have made the plants less sensitive to water stress, leading to similar yields as compared to full irrigation. Fereres and Soriano (2007) reported that for maize, wheat and sunflower, the harvest index (the fraction of the biomass that is harvested) remained constant with biomass production until about 60% of maximum biomass after which the harvest index decreased. Therefore, they concluded that deficit irrigation should attempt to meet irrigation requirements that produced at least 60% of maximum biomass.

Surprisingly, however, yields and water use efficiency can also improve with deficit irrigation. Crops such as sorghum and cotton produce maximum harvest indexes when subjected to mild to moderate water stress, so maximum water productivity and crop production can be achieved by irrigating below full water requirements (Fereres and Soriano, 2007). For spring wheat in Gansu Province, an arid area of China, regulated deficit irrigation treatments increased the yield by 16.6 to 25% with a reduction of 14 to 22.9% in water use (Zhang *et al.*, 2006). Similarly, maximum yields, water use efficiency and harvest index for winter wheat in the Loess Plateau, a semi-arid region in the northwest of China, occurred when the crop was subjected to mild and severe soil drying in the early vegetative and maturity stages, respectively. Further, grain yields did not increase when the evapotranspiration exceeded a critical value of 88% of the measured maximum evapotranspiration, even with maximum water applications, because of the quadratic relationship between grain yield and evapotranspiration (Kang *et al.*, 2002). Lastly, Zwart and Bastiaanssen (2004) concluded that the optimum values for crop water productivity for wheat and maize are reached at roughly 150 and 280 mm of irrigation water, respectively, so there are opportunities to maintain or increase agricultural production of these two crops with less irrigation water than is currently applied.

In summary, deficit irrigation has several advantages and constraints. First, the water use efficiency of a farm or irrigation district can be increased by diverting the saved water to other crops or to increase the irrigated area to compensate for any reductions in yields (Kirda, 2002). Second, the quality of the yield (for example, sugar content and grain size) can be equal or even superior than in rain-fed and fully irrigated agriculture (Geerts and Raes, 2009). However, the success of deficit irrigation depends on having a good understanding of a crop's response under water stress to identify the growth stages when water application restrictions might be feasible (FAO, 2002). Furthermore, to practice deficit irrigation, irrigators require access to a minimum irrigation amount at all times and unlimited access to water during sensitive growth stages (Geerts and Raes, 2009).

2.2.4 Irrigation Efficiency Improvements in Alberta

In Alberta, on-farm application efficiency (defined as the percentage of water diverted to on-farm systems that actually becomes available for crop use) was estimated to have increased from approximately 60% in 1990 to 71% in 1999 and projected to approach 78% with additional technology gains (Irrigation Water

Management Study Committee, 2002a). The gradual shift from surface irrigation to wheel move and centre pivot sprinklers has improved irrigation application efficiencies. Similarly, the irrigation district water use productivity (defined as the commodity yield per unit area divided by the volume of water diverted per unit area) has followed an increasing trend in the last three decades (Figure 12). These improvements in water use productivity have been a result of increasing crop yields and increasing efficiencies.

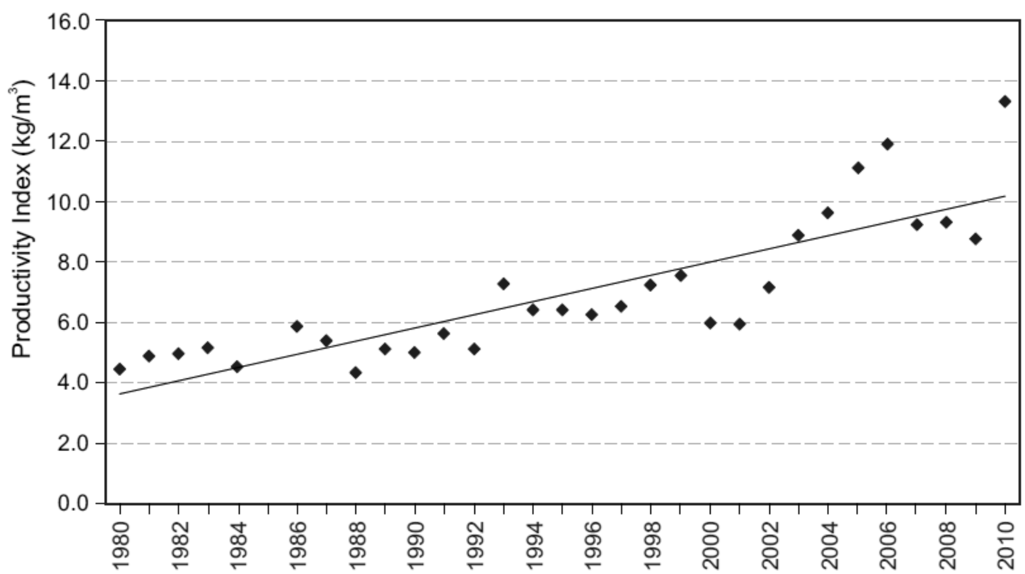


Figure 12 Irrigation District Water Use Productivity from 1980 to 2010 (Alberta Agriculture and Rural Development, 2011)

Further water use efficiency gains through the adoption of more efficient irrigation technologies are unlikely to occur to the extent desired in Alberta's *Water for Life* strategy (Nicol *et al.*, 2008). First, the main drivers of adoption have been to increase yields and ensure water supply security during drought, not the perceived need to save water (Nicol *et al.*, 2008; Bjornlund *et al.*, 2009).

Second, the trend in adoption has slowed down – a tendency that is likely to continue because high levels of subsidization or major commodity price increases would be necessary to encourage irrigators to invest in new technologies (Nicol *et al.*, 2008; Bjornlund *et al.*, 2009). Adoption of more efficient technologies is also impractical for some farms. In any case, managers in the irrigation sector believe that only small gains in water efficiency are possible, and that these can be best made by modifying existing equipment as opposed to encouraging changes in management practices (Bjornlund *et al.*, 2007). Yet, better water management practices, such as monitoring soil moisture, paying close attention to the water needs of the crop and employing irrigation scheduling tools have high potential for water savings (Nicol *et al.*, 2008; Bjornlund *et al.*, 2009).

2.3 Irrigation Models

Since achieving efficiency gains requires a good understanding of the potential benefits of improved management practices and the variability of factors that influence irrigators' decisions, a variety of simulation models have been developed to permit assessment of alternative irrigation management practices. These models estimate crop evapotranspiration and irrigation requirements, perform soil water balance calculations, assess the effects of different management options, optimize reservoir operations and crop mixes, and evaluate the relationships between water stress and crop yields. Models vary in scale, location of the study area, complexity with which crop growth is simulated, method used to allocate water, extent to which the operation of the irrigation system components are modelled, and overall purpose.

Different researchers have grouped irrigation models into different categories distinguishing between models that (1) support strategic decision-making and planning, (2) optimize irrigation water allocation to maximize output and water use, or (3) support operational tasks like irrigation scheduling and water delivery (Mateos *et al.*, 2002; Lecina and Playán, 2006a; De Nys *et al.*, 2008; Ali, 2011). This section reviews three approaches to modelling irrigation projects: planning, optimization and decision support tools. The basis for sorting into these three categories was the model's primary function, as well as previous classifications in the literature. Planning models inform seasonal and long-term strategic management decisions, while focusing primarily on total water demands. Optimization models focus on maximizing economic benefits under a variety of physical and resource constraints. Decision support models support a wide range of "what if" scenarios and, since they typically incorporate more processes than planning models, they can also be used to inform seasonal operational and scheduling decisions by irrigation managers and irrigators themselves. Finally, this section discusses a suite of models developed for irrigation in Alberta.

2.3.1 Planning

One group of models has been developed to address questions about planning for irrigation projects. These models are concerned with estimating total water demands under different physical factors – for example, soil types and climatic data – and management scenarios, such as cropping patterns, reservoir operations, and irrigation scheduling options. The common characteristic of this type of model is a focus on determining total water demands by aggregating irrigation water requirements. The Irrigation Demand Model (IDM) falls into this category because its main purpose is to calculate total irrigation demands for potential changes in infrastructure and cropping patterns in the irrigation districts in Alberta, as will be discussed in later sections.

Chávez-Morales *et al.* (1992) developed a simulation model for planning the management of Irrigation District No. 38 in Sonora, Mexico. The model computes water and other resource requirements for a specified cropping pattern, as well as the resulting profits. Additionally, the model simulates the operation of the system reservoir based on the reservoir and canal network capacities, evaporation and precipitation, and the water requirements for irrigation.

Yamashita and Walker (1994) validated the “unit command area” (UCA) model which predicts crop growth, daily water demands and yield responses for individual command areas – aggregations of fields served by a single canal turnout – and simulates water allocation between the fields. A comparison between cumulative water demand curves produced by the model and the actual supply hydrographs for the Abraham Irrigation Company in Utah, USA, showed that the model performs well for long-term (seasonal) demand predictions of large command areas. However, the model is less suitable for planning in smaller command areas.

Prajamwong *et al.* (1997) developed the 'Command Area Decision Support Model' (CADSM) to study the effects of water management practices on an irrigated area for planning and evaluation purposes. The model determines daily crop water requirements and simulates water distribution among the irrigated fields. A statistical method generates weather data based on mean and standard deviation climatic data. The number and size of fields are also statistically generated based on the prevalent cropping pattern. The model uses a daily water-balance method to calculate water amounts in each soil layer. Evapotranspiration and yield reductions due to water deficits, soil water-salinity or over-irrigation are estimated using the method outlined by Doorenbos and Kassam (1979). Lastly, the model applies a queuing algorithm to allocate water deliveries using one of three types of irrigation schedules: on-demand, fixed rotation and continuous flow. The model accurately simulated cumulative supply hydrographs for two study areas in Delta, Utah and Thailand. However, actual and modelled instantaneous supply hydrographs differed because the model does not account for actual lag times in the conveyance system and other factors that are important to the daily or weekly operations. The model was recommended for seasonal planning rather than daily or weekly operations planning.

Leenhardt *et al.* (2004) focused on estimating irrigation demand at a regional scale. Their model ADEAUMIS estimates actual water demand for irrigation for short term applications in a large area in France. The model simulates plant development and actual irrigation practices based on a database of climatic variables and information on the common farm management practices used in the region. The model simulates realistic patterns of water withdrawals to be used for real-time water management, especially during non-standard years.

De Nys *et al.* (2008) developed WaDI (water delivery for irrigation) to guide strategic decision making in irrigation schemes. The model focuses on the interaction between water supply and demand. It consists of a simple representation of the water distribution network and the organizational constraints that govern the system. The model calculates water demands, water supply and response factors from the farm level to the pumping plant. The modelled scenarios in the study by De Nys *et al.* (2008) investigated the effects of (1) changes to irrigation scheduling and (2) infrastructural changes to increase conveyance efficiency and storage capacity in two irrigation schemes in Brazil. Two limitations were identified in the model: the model does not include water demand data and it does not represent the feedbacks between supply and demand. Nonetheless, WaDI helped stakeholders to gain a better understanding of the relationships between water supply and demand, and to explore the effects of investments in infrastructure and other management changes.

2.3.2 Optimization

The goal of a second group of models has been to find optimal solutions to water allocation, cropping patterns and the operation of irrigation systems. These models have used optimization algorithms to identify best possible management options. In general, the goal of the optimization approach has been to maximize water allocation and profit from crop yields under a set of constraints or to find the most efficient irrigation scheduling and delivery options.

A subset of this group of models has focused on the optimization of rotational water allocation networks. Suryavanshi and Reddy (1986) used linear programming to optimize the sequencing of outlet operation for 'constant frequency-variable depth' rotational systems. Later, Khepar *et al.* (2000) developed a model to account for seepage losses in the conveyance system to ensure equitable distribution of water between farmers in the upper and lower halves of a watercourse in rotational systems in Punjab, India.

Kuo *et al.* (2000) developed a genetic algorithm-based model to optimize water distribution in an irrigated area to different crops to maximize profit for a growing season under area and water supply constraints. The tool simulates the daily on-farm soil water balance, evapotranspiration and irrigation application amounts, and relative crop yields and then uses them as inputs for a genetic algorithm module that maximized the projected net economic benefit. The model was applied to an irrigation project in Delta, Utah to maximize crop production benefits.

Shangguan *et al.* (2002) focused on optimal allocation of water resources for irrigation at the regional scale (6860 ha of cultivated fields) for the semi-arid region of Yangling on the Loess Plateau, China, based on deficit irrigation principles. Their approach ensured that water allocation first maximized the ratio of actual to maximum yields during different crop growth stages, then for multiple crops based on the maximum total benefit of a sub-unit of the region, and finally among all sub-units based on the maximum combined benefits. The model successfully represented two common practices: first, periods with large yield sensitivity to drought were prioritized; and second, the crop pattern (grain crops versus cash crops) was sensitive to net economic benefits.

Ali *et al.* (2003) combined an optimization model with a Geographic Information System (GIS) to solve for the optimal reservoir operating policy of an irrigation project in Malaysia for dry and wet seasons where the shortage of reservoir water was the main constraint to the stability of the project.

Georgiou and Papamichail (2008) used non-linear programming to determine the optimal reservoir release policies, the irrigation allocation to multiple crops and the optimal crop pattern under various weather conditions for an irrigated area served by a reservoir on the Havrias River in Northern Greece. The model maximizes the total farm income using the cultivated area and water allocated to each crop as the decision variables. Different weather conditions are created by running the model for different probabilities of exceedence of stochastic rainfall, evapotranspiration and reservoir inflow.

2.3.3 Decision Support Tools

A third group of models is better suited to explore "what if" questions than the models in the first two groups; they are meant for decision support. These models integrate modules that simulate the complex interactions between on-farm crop growth and water balance processes, the operation of the conveyance infrastructure, irrigation scheduling options, and the effects of water management practices on crop yields. The strength of the tools in this category is the intricate way in which the factors that affect irrigation water management are modelled. These models combine a simple simulation of crop water requirements – using a methodology similar to Smith (1992) – with options for irrigation scheduling and delivery. The models differ based on whether they focus on representing irrigation management decisions (Mateos *et al.*, 2002; Lecina and Playán, 2006a; Smith, 1992) or farmer's behaviour (George *et al.*, 2000; Bazzani, 2005).

CROPWAT, developed by the FAO, is a widely known computer program used for the design and management of irrigation schemes (Smith, 1992). The model calculates reference evapotranspiration and crop water requirements based on the guidelines developed by Doorenbos and Pruitt (1977). The program includes a range of irrigation scheduling options that make it an attractive tool for the analysis of irrigation schedules when crop water requirements cannot be fully met. Since CROPWAT was used in this research, the model will be discussed in more detail in section 3.3.2.

A more comprehensive decision support system, the scheme irrigation management information system (SIMIS), was developed by the FAO to aid irrigation managers in finding satisfactory rather than optimal management solutions (Mateos *et al.*, 2002). The SIMIS model involves two modules – water management and financial management – each with sub modules that work in an integrated manner. In the water management module, crop water requirements are calculated using the approach by Smith (1992). The model can be used to compare net irrigation requirements with network capacities and to simulate different irrigation scheduling options. Only approximate water delivery schedules can be determined because travel times in the distribution system are estimated. Lastly, this module records actual water applications. The financial management module allows managers to keep accounting records, manage water fees and track maintenance activities. An important feature of the model is the performance indicators module that calculates water distribution, agricultural intensity, maintenance, and financial indicators for the assessment of the irrigation scheme. The main limitation of applying SIMIS to a district like the WID would be to adapt the available data into the data sets required in the model. The validity of the approaches used in the model is still being assessed by applying the model to test cases as reported in Mateos *et al.* (2002).

Bazzani (2005) developed the Decision Support System for Irrigation (DSIRR), a tool that integrates irrigation processes and agronomic aspects at the farm level with economic theory to represent the complexities of farmers' behavior. The model simulates decision processes at the farm level using multicriteria analysis and aggregates the farms to evaluate environmental impacts at the catchment level. The DSIRR performs two kinds of analysis: short term (to simulate pre-season decisions on crop mix, irrigation scheduling and labour) and long term (to simulate the period in which farmers can completely change their farm structure and invest in new irrigation technologies). The model's economic indicators inform policy development by exploring the trade-offs between conflicting objectives. Current applications of the model have been under the EU's Water Framework Directive.

Lecina and Playán (2006a) developed a decision support system, Ador-Simulation, capable of simulating water flows in an irrigation district. The model consists of five modules that simulate on-farm water and hydrosaline balances, the conveyance and irrigation systems, and water allocation within the district. Surface irrigation is modelled numerically accounting for spatial variability of soil properties within the plots. Crop growth and water requirements are modelled using the methodology by Smith (1992). The water conveyance module aggregates water demands and compares them to the capacity of the distribution network. Lastly, the model simulates water allocation within the district according to a set of rules that consider network capacity and reservoir storage. An important addition to previous models is that this model can be used to assess the effects of modernization of the conveyance and drainage systems in addition to changes in management practices and cropping patterns. The model was calibrated, validated and applied to the Irrigation District V (Five) of Bardenas, Spain where the observed and modelled water demand differed by less than 2% (Lecina and Playán, 2006b). The application of the model to simulation scenarios identified two potential approaches to reducing water demand: through a reduction in the irrigation time and by improving irrigation structures to increase the reuse of return flows.

Finally, a subset of the decision support tools was developed as irrigation scheduling tools for farmers. George *et al.* (2000) developed an irrigation scheduling model with two components: soil water balance and crop yield. The model determines irrigation schedules based on user-defined root growth functions, crop stress factor, effective rainfall, ET estimation methods, and irrigation scheduling criteria. The model was tested for field data and performed similarly to CROPWAT. An important strength of this model is the emphasis on providing a user-friendly interface that facilitates farmer adoption.

2.3.4 Irrigation Models in Alberta

In Alberta, a suite of modelling tools has been applied to study irrigation water demand and supply, starting from the calculation of crop water demands and diversion requirements at the field and district level, to the allocation of water for irrigation at the basin-scale level, and finally, the analysis of the financial implications of water availability on typical farm enterprises across the basin (Ali *et al.*, 2010). The first model, the Irrigation Demand Model (IDM) is a tool used to determine irrigation water requirements based on crop growth parameters and the associated district diversion requirements necessary to supply that demand (Irrigation Water Management Study Committee, 2002a). The IDM will be discussed in detail in Chapter 3. A second model, the Water Resources Management Model (WRMM) is a surface water allocation model based on linear programming developed by Alberta Environment as a planning tool for the South Saskatchewan River Basin (Alberta Environment, 2002b). The WRMM takes the irrigation requirements calculated by the IDM and determines whether they can be supplied based on all major storage reservoirs, diversions, water uses, and apportionment commitments including non-irrigation sectors (Irrigation Water Management Study Committee, 2002a). The WRMM is in essence an optimization model for the basin. Note that the WRMM conducts reservoir operation calculations, while the IDM does not.

These two models can be used together to determine irrigation deficits. In the simulation, a deficit is defined as the difference between the demand calculated by the IDM and the water that the WRMM determines that could be available to irrigation based on license priorities and other uses across the basin. These deficits form the input to a third model, the Farm Financial Impact and Risk Model (FFIRM) which estimates the financial impact and risk associated with water supply shortages for five representative farm types in six different agro-climatic regions (Irrigation Water Management Study Committee, 2002c). The first component of the FFIRM model determines the optimal allocation of water between fields in a farm to maximize revenue based on calculated yields for each crop. The second component tracks farm assets and liabilities over time to determine the farm's financial performance. Note that the main difference between the approach used in this research and the FFIRM is the focus on the effects of imposed water deficits at the district versus the farm level, respectively. Additionally, the yield calculations in the FFIRM are based on relatively old empirical crop water and yield relationships – as discussed in later sections – while this research used more recent empirical relationships.

At the farm level, the Alberta Irrigation Management Model (AIMM) was developed to help producers in their irrigation scheduling decisions (Alberta Agriculture, Food and Rural Development Irrigation Branch, 2011). The model determines crop water use and irrigation application amounts using a water balance approach and predicts irrigation applications in the near future. The input required includes field size, irrigation system information, crops grown, planting date, climatic inputs, soil information, and daily irrigation applications. Additionally, the AIMM can be used to record information on crop production and farm management.

2.4 Modelling the Effects of Water Stress on Crop Yields

2.4.1 Crop yield and water relationships

Many researchers have studied the relationship between yield and crop water use to quantify the effect of reduced water supply on crop production. Simple linear expressions that relate crop dry matter yield and evapotranspiration have been proposed, where the slope of the function depends only on the sensitivity of the crop type to water stress (Jensen, 1968; Stewart and Hagan, 1973; Doorenbos and Kassam, 1979; Stewart *et al.*, 1977; Howell, 1990).

Howell *et al.* (1990) noted that the effects of irrigation on crop yields are complex and depend on many site-specific factors, including irrigation application uniformity and efficiency. The relationship between yield and irrigation application is convex because irrigation efficiency typically decreases as ET_m is approached (Stewart and Hagan, 1973) due to non-ET losses (percolation, soil water evaporation and soil storage) which occur at excessive irrigation applications (Tolk and Howell, 2008).

In a widely-cited FAO Drainage Paper, Doorenbos and Kassam (1979) applied the Stewart *et al.* (1977) method to quantify the yield response to water. The approach has since been used extensively because of its reasonable accuracy and its requirements for relatively few quantities, all of which are easily-measured or calculated. The method’s key equation linearly relates the ratios of actual yield

(Y_a) to maximum yield (Y_m) and actual evapotranspiration (ET_a) to maximum evapotranspiration (ET_m) as shown in Equation 5:

$$1 - \frac{Y_a}{Y_m} = k_y(1 - \frac{ET_a}{ET_m}) \quad \textbf{(5)}$$

where the yield response factor, k_y, is empirically derived for a specific crop type and growing conditions. The yield response factor is similar to the crop coefficient, K_c, in that both are based on experimental data and vary depending on crop type. This method assumes that water is the only yield-limiting factor and that the linear relationship between relative yield and relative evapotranspiration is valid for water deficits up to 50%. Since the yield is actually also affected by other factors (crop variety, fertilizer, salinity, pests and diseases), the relationships apply to crops growing under optimum agronomic and irrigation practices. The yield response factor indicates the sensitivity of crop yield to water supply; a crop with a higher k_y value will suffer more under water stress than one with lower k_y value, and should therefore be given priority under conditions of limited water supply. The value of k_y actually changes throughout the growth season, since the sensitivity of a plant to water shortage varies with its developmental stage. In general, crops are more sensitive to water stress during emergence, flowering and early yield formation than during early (vegetative, after establishment) and late growth periods (ripening) (Doorenbos and Kassam, 1979). However, a single value of k_y is typically used to represent the effects of water deficit for the entire season when data on the individual crop growth stages is not available.

Additionally, the maximum yield and evapotranspiration depend on the growing environment, so relationships are regionally specific.

Although crop water production functions are usually simplified into a linear form, the crop production function in reality has a logistic shape with a central linear portion and a mild to sharp slope, and decreasing slope as the function reaches relative evapotranspiration close to 1 (Geerts and Raes, 2009), as seen in Figure 13. The function drops below a relative evapotranspiration of 1 because if too much water is applied, the yield might decline as a result of water logging or leaching of nutrients. Rather than a linear shape, Hexem and Heady (1978) found that quadratic, square root and three-halves polynomials adequately described the relationships between yields, water and fertilizer applications for corn, cotton, wheat, sugar beets, and corn silage. Thus, crop water production functions can exhibit linear, convex or concave quadratic shapes depending on the crop type, as summarized in Geerts and Raes (2009). They concluded that the sensitivity of different crops to water stress also varies with growth stage, genotype and location. Zwart and Bastiaanssen (2004) added, for irrigated wheat, rice, cotton and maize, that the large range of published values for crop water productivity – the ratio between the actual marketable crop yield and the observed seasonal crop water consumption – is due to differences in climate, irrigation management practices and soil management. Hence, water is just one of many factors to consider when studying crop yields under different agronomic management practices.

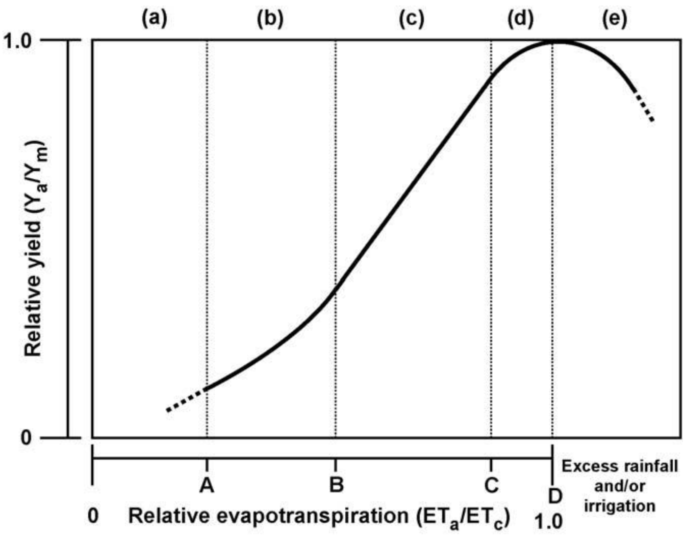


Figure 13 Generalized shape of the relation between relative yield and relative evapotranspiration. Five sections of various lengths may be distinguished. In section (a) insufficient water results in low-quality yields; in sections (b) and (c) yields and water productivity increase with increased water supply in a concave (b) or linear (c) way; in section (d) the slope decreases so that proportional yield increases per unit ET gradually level off; and finally, in section (e) applying excessive water (ET_a/ET_c>1) can lead to yield reductions (Geerts and Raes, 2009)

For southern Alberta, Palmer *et al.* (1982) developed empirical relationships between crop water supply and crop yield from collected experimental data for ten crops grown in the region. The crop yield equations are quadratic and relate the actual yield relative to the maximum yield obtained in the experiments (Y_p) and the ratio of actual evapotranspiration to the maximum evapotranspiration recorded in the experiments (ET_p). Figure 14 shows the empirical relationships for alfalfa and barley as an example. Similarly, they developed experimental relationships between the relative yield and the evapotranspiration for specific months relative to the potential evapotranspiration for the total season to assess the effect of water stress during different plant growth stages.

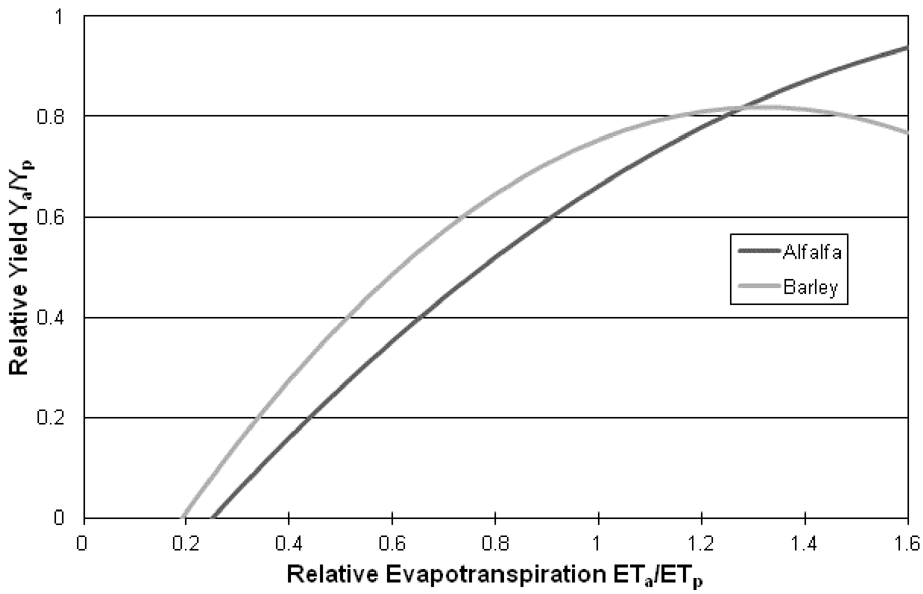


Figure 14 Empirical relationships between crop yield and crop water requirements for alfalfa and barley for southern Alberta (Palmer *et al.*, 1982)

More recently, Bennett and Harms (2011) used published values of k_y to develop relationships between crop yield and water requirements for eleven major irrigated crops in Alberta, based on the methodology of Doorenbos and Kassam (1979). Table 1 shows the parameters used to develop the crop yield and water requirement relationships for those crops grown in the WID. Note that their relationships are based on maximum reported yields for the region and maximum evapotranspiration values that correspond most closely to conditions near Lethbridge, Alberta. Therefore, the yield values they produce are likely to be higher than those expected in the more northern WID, with its lower heat unit values and potential evapotranspiration. Also note that Bennett and Harms (2011) provide a brief discussion of the studies in the literature on which they base their values, but do not provide coefficients of determination (R^2) for the yield response factors. This is a significant limitation in applying the relationships to calculate potential yield reductions because the reliability of these relationships for conditions in southern Alberta is unknown.

Table 1 Maximum crop evapotranspiration, maximum potential yield, yield response factor, and relationship between crop yield and ET for crops grown in the WID (Bennett and Harms, 2011)

Crop	Maximum crop evapotranspiration ET_m (mm)	Maximum potential yield Y_m (Mg/ha)	Yield response factor (k_y)	Relationship between crop yield and ET
Alfalfa (Hay)	747	18	1.05	$y = 0.025ET_a – 0.90$
Barley	447	7.3	1.15	$y = 0.019ET_a – 1.10$
Barley silage	413	31.4	1.15	$y = 0.087ET_a – 4.71$
Canola	476	3.9	1.15	$y = 0.009ET_a – 0.58$
Corn Silage	544	44.8	1.25	$y = 0.103ET_a – 11.20$
Grass (Hay)	539	13.4	1.05	$y = 0.026ET_a – 0.67$
Hard Spring Wheat	550	7.8	1.15	$y = 0.016ET_a – 1.17$
Potato	599	67.2	1.10	$y = 0.123ET_a – 6.72$

2.4.2 Models

Several simulation models have been developed to find optimal irrigation schedules for maximum yields and to simulate the effects of water stress on yields, including the effect of deficit irrigation. Some of the models described in section 2.3 incorporate yield calculations but their attention is on all aspects of irrigation water management; whereas the models described in this section focus primarily on crop yields.

Classical irrigation scheduling tools have been combined with linear crop water functions to estimate the effect of water deficits on yields. CROPWAT, introduced earlier, incorporates yield response factors from Doorenbos and Kassam (1979) to estimate yield reductions per season and per growth stage with the implementation of different irrigation schedules (Smith, 1992). Different approaches have been used in past studies of deficit irrigation using CROPWAT. In particular, CROPWAT adequately predicts the yield reduction as a result of deficit irrigation scheduling and reflects the sensitivity to crops during various growth stages, but it requires calibration of the main crop parameters – crop coefficient, critical depletion factor and yield response factor (Smith *et al.*, 2002). Smith *et al.* (2002) compared measured yield reductions obtained from experiments of deficit irrigation treatments with the yield reductions calculated with CROPWAT by reproducing the dates and the application depths of each irrigation event according to the deficit irrigation treatments. The treatments consisted of withholding irrigation applications until the soil moisture content was depleted to 20-25% of the total available soil moisture in the root zone. Crops were also subjected to deficit irrigation by imposing water stress in one or more growth stages. Smith *et al.* (2002) assessed the effect of the irrigation schedules on crop yields in CROPWAT by evaluating the cumulative yield reductions during the growth stages and they determined that CROPWAT accounted well for the relative sensitivity of different growth stages to water stress.

Raes *et al*. (2006) combined the soil water balance model BUDGET with the k_y approach to simulate the effect of water stress on yields, producing satisfactory results compared to observed yields for winter wheat and maize as determined by small root mean square error values between 7 and 9%. In the simulation, the effect of water stress on yields during the various growth stages was combined to find the total yield for the season.

Other models have used more sophisticated approaches to simulate crop growth, development and yields under deficit irrigation. PILOTE 1.3, a water balance model calibrated for sorghum and sunflower in France, predicts actual evapotranspiration and yields as a function of leaf area index (LAI), which is determined from the water stress index and thermal time calculated from air temperature (Mailhol *et al.*, 1997). AquaCrop, a second model developed by the FAO, incorporates an improved understanding of the relationships between the physiological and agronomic processes behind the response of crop productivity to water deficits (Steduto *et al.*, 2009). The model separates evapotranspiration into evaporation and transpiration, and calculates yields as the product of final biomass – which is a function of transpiration and water productivity – and harvest index (Raes *et al.*, 2009). AquaCrop has been parameterized, tested and applied successfully to create guidelines for deficit irrigation water applications for quinoa in the Central Bolivian Altiplano (Geerts *et al.*, 2010) and for maize with field experiments at Davis, California (Hsiao *et al.*, 2009). Note that the FAO still endorses the use of CROPWAT for irrigation schemes because it addresses a wide range of irrigation water management issues, while AquaCrop focuses primarily on crop yields. A third model, Daisy, is a well-tested model developed in Denmark that simulates nitrogen dynamics and inter-cropping systems in addition to the water dynamics in the soil that influence crop production and crop yields (Abrahamsen and Hansen, 2000). APSIM, a modelling framework developed in Australia, estimates yields in response to management in farming systems (Keating *et al.*, 2003). APSIM's wide-ranging applications include studies of crop management and species interactions, and long-term impacts of farming on soil quality. Finally, the Decision Support System for Agrotechnology Transfer Cropping System Model (DSSAT-CSM) simulates crop growth, development and yield of a crop growing on a uniform area of land under different management options (Jones *et al.*, 2003). DSSAT-CSM simulates field operations such as planting, harvesting, fertilizer applications, and irrigation, and it can be used to study crop production under climate variability. The model's modular structure and ability to study crop systems make it suitable for a range of agronomic applications. DSSAT-CSM was re-designed from the Decision Support System for Agrotechnology Transfer (DSSAT) which has been applied around the world for agronomic research.

In addition to agricultural variables, some models have incorporated other physical, social and economic factors that influence crop yields. Jalota *et al.*

(2007) used output from CroPMan, a physical model that simulates crop growth and yields under various irrigation and agricultural management options, to develop yield response functions under various levels of irrigation water and precipitation. These were combined with a model of farmers' decision-making preferences to investigate the impact of increasing water costs in Punjab, India. Further, crop production functions that included socio-economic factors like gross added value of agriculture and irrigated area, in addition to water use, were developed for major crops in the Ebro basin of Spain using regression analysis (Quiroga *et al.*, 2011). Labbé *et al.* (2000) used IRMA to model farmers' irrigation decisions and practices in the Charente river basin in France, where irrigation is partially restricted during water shortages. The model consists of three components that describe farm characteristics, define the rules used to implement irrigation and assess the effects of those decisions through a classic water balance model combined with a crop yield function. Modelled and measured volumes delivered to three representative farm during two irrigation seasons differed by less than 8.5%.

In the Farm Financial Impact and Risk Model (FFIRM) discussed earlier, yield calculations are based on the empirical quadratic crop yield equations developed by Palmer *et al.* (1982) (Irrigation Water Management Study Committee, 2002c).

In summary, the models presented in this section simulate crop growth and the effects of water stress on yields to different levels of detail. Models which use the

k_y approach (CROPWAT and BUDGET) simulate the effect of water stress on yields in a simple, yet effective, way. They require few parameters and could be calibrated with existing crop data for southern Alberta. CROPWAT is a reasonable choice because of its wide application, good documentation and availability to be used as free software. Models like PILOTE, AquaCrop, Daisy, APSIM, and DDSAT-CSM are more suitable for detailed agronomic research than for a first-order estimate of district-wide changes in management. Evidently, these models would require calibration of more parameters based on experimental data – some of this data may not be available for southern Alberta. They would provide better estimates of crop yield reductions under deficit irrigation, but at the expense of more data requirements. Finally, models that incorporate other physical, social and economic factors (Jalota *et al.*, 2007; Quiroga *et al.*, 2011; Labbé *et al.*, 2000) are interesting because they integrate a broader set of parameters that influence crop yields (crop prices, farmers' decisions, farm characteristics, etc). The FFIRM model could be used for this purpose in Alberta. The model is currently being updated with new crop yield and water requirement relationships and other input data but it meant for internal use by Alberta Agriculture and Rural Development only (personal communication, Rod Bennett, July 2012).

3 Methodology

This chapter presents the research methodology. Section 3.1 describes the Irrigation Demand Model (IDM) in detail. Section 3.2 describes the steps taken to simulate the rehabilitation of WID infrastructure and implementation of most efficient irrigation technologies scenario. Finally, Section 3.3 outlines the methods used to simulate the water restriction scenario. This last section is divided into two parts: the first part describes the simulations carried out with IDM output; while the second part provides a brief review of CROPWAT and describes how it was used for supplementary simulations of the water restriction scenario.

3.1 Irrigation Demand Model

The Irrigation Demand Model (IDM) is a simulation tool developed by Alberta Agriculture and Rural Development (ARD) and the Alberta Irrigation Projects Association (AIPA) to determine irrigation water demands for the thirteen irrigation districts in the province (Irrigation Water Management Study Committee, 2002b). The IDM determines total annual water volumes associated with irrigation by adding system losses to the evapotranspiration crop demands (Figure 15).

The model has been applied to planning and policy development for the irrigation sector. ARD has used the IDM to support analysis of current and future irrigation water use, in particular through simulations involving the rehabilitation of the districts' conveyance systems, changes to crop patterns and irrigation efficiency, and expansion of the irrigated area. The model was developed with input from the irrigation districts but it was not intended for district use; it is better suited for long term planning as opposed for short term management.

The IDM is composed of two main modules, the Irrigation Requirements Module and the Network Management Module, and uses a comprehensive database of the districts' infrastructure, crop and irrigation technology information, as well as historical weather data. Figure 15 shows the input, modules and output associated with a simulation run in the IDM. A detailed description of the model and its use can be found in Irrigation in South Saskatchewan River Basin: 21st Century Volume 4 Modelling Irrigation Water Management (Irrigation Water Management Study Committee, 2002b). The main components of the model and the relevant processes associated with the simulation work conducted for this thesis are reviewed below.

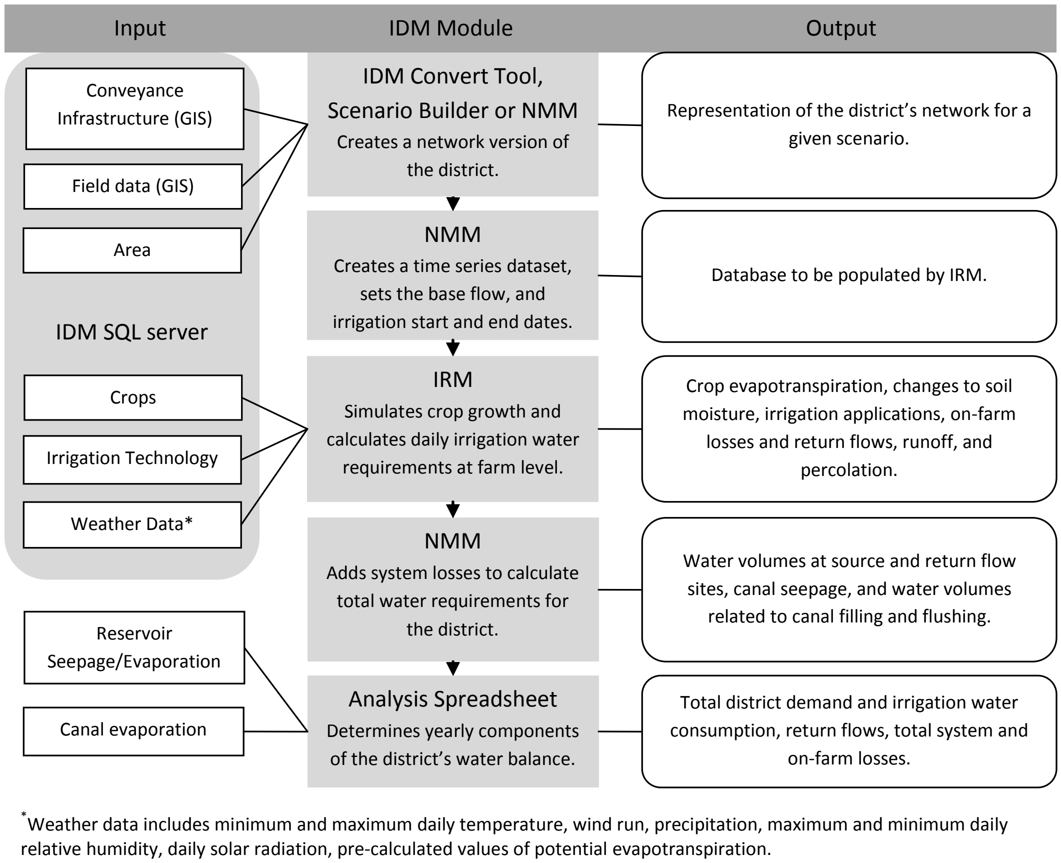


Figure 15 Steps involved in a simulation using the Irrigation Demand Model (adapted from Irrigation Water Management Study Committee, 2002b).

3.1.1 Database Overview

The IDM accesses data stored in the Local Operating Database implemented in Microsoft SQL server to simulate the operation of a water distribution network. Key components of the database include:

- *Weather Data.* The weather dataset contains daily values of precipitation (millimetres) and various parameters required to calculate potential evapotranspiration: maximum and minimum temperature (Celcius), wind run per day (kilometres), maximum and minimum relative humidity (%), and solar radiation (kilojoules per day). Calculated values of evapotranspiration (millimetres) using the Priestley-Taylor equation (Priestley and Taylor, 1972) are also included. The Priestley-Taylor coefficient used in the calculations was modified from 1.26 to 1.7 to improve the equation's computation of evapotranspiration under semi-arid conditions as suggested by Jensen *et al.* (1990) (personal communication with Robert Riewe, ARD, November 21, 2011). Weather parameters at the time of the research were available from 1927 to 2009.

- *Crop Data.* The crop dataset includes the parameters that define crop development and water requirements for fifty crops commonly grown in southern Alberta. The data includes: crop type; minimum and maximum root depths (millimetres); planting, cover, harvest and cut dates relative to wheat planting date (Julian Day 120); irrigation threshold (%); random seeding range; and crop coefficient curve. The irrigation threshold is the soil moisture relative to the maximum soil moisture that will prompt an irrigation application. The random seeding range defines the number of days before or after the normal planting date when the crop will be planted if the random seeding date flag is on. The crop coefficient curves consist of daily values of the crop coefficient (K_c) for Julian days 105 to 288. Figure 16 shows a plot of the crop coefficient values as defined in the IDM for alfalfa 2 cut and barley silage as an example – note that the crop coefficient curve for alfalfa 2 cut shows two drops at the two cutting dates and assumes that the crop continues to grow after the second cut. The daily crop coefficient is used to adjust the potential ET to account for the crop's growth stage as in Equation 1.

Figure 16 Crop coefficient curves as defined in the IDM database for alfalfa 2 cut and barley silage

- *Irrigation Equipment Data.* The irrigation equipment dataset contains the parameters that describe the operation and water requirements of forty irrigation methods commonly used in the region including gravity, sprinkler and micro irrigation systems. These are based on standard or commonly observed operating conditions and configurations in the region. The data includes: system type, water usage rate (l/s), application efficiency (%), return flow factor (%), coverage rate (hectares/day), down time per day (minutes/day), and precipitation cut-off (mm). The water usage rate is the rate at which the irrigation system removes water from the district distribution network. The application efficiency indicates the portion of the water from the distribution network that is absorbed by the soil. The return flow factor indicates the portion of the water that is not absorbed by the soil and returns to the irrigation system or river basin. The coverage rate defines the area of land that can be irrigated in one day used to determine the number of days needed to irrigate a field. The down time per day represents the amount of time that the irrigation system does not take water from the distribution network (for example, the amount of time needed to move the equipment to a different portion of the field) and it is used to calculate the unused volume of water that flows through the distribution network as a result of system down time. Lastly, the precipitation cut-off indicates the amount of precipitation that would cause an irrigation event to stop.

- *Soil Data.* The IDM defines three soil types: fine, medium and coarse. They differ based on the soil moisture capacity (210, 180 and 120 mm per metre depth, respectively).

- *Conveyance System Data.* The IDM database contains data from the Alberta Agriculture Geographic Information System (GIS) that describes the configuration of a district's network. The GIS database is updated annually using information provided by the irrigation districts. The data is used to represent irrigation networks within the NMM by using ESRI MapObjects Shape Files. These files describe the characteristics of the network components (conveyance work segments, diversions, spill-ways, and tail-outs) including their geographic information (such as the length and path of canal segments) and attribute data (for example, type of construction, capacity and seepage rate), and how they are connected to each other. Details on how the data is used to generate a network representation in the NMM can be found in the model's documentation (Irrigation Water Management Study Committee, 2002b).

- *Field Data.* The field dataset describes the characteristics of the parcels of land that will be simulated such as the area, physical location, soil type, crop type, and irrigation system type.

3.1.2 Network Management Module (NMM)

In the IDM, an irrigation district is modelled as a network of conveyance works that supply water to farm-scale irrigation systems on a demand basis. The Network Management Module (NMM) aggregates water demands throughout the district conveyance network, assuming that supply is not a constraint (Irrigation Water Management Study Committee, 2002b).

The NMM simulates an irrigation water distribution network by assembling a variety of components: canal segments, closed pipe segments, diversions, junctions, control gates, irrigation demands, runoff collectors, base flows, a system source, and a system sink. Each of these components has parameters that determine their operation. The data that defines the components for a particular irrigation district comes from the Alberta Agriculture Geographic Information System (GIS).

I. Setting up an NMM simulation

Several steps are involved in preparing a simulation run with the NMM. First, a network version is created in the Local Operating Database using the IDM DB Convert tool. A network version is a representation of the state of an irrigation district's water supply infrastructure and its on-farm systems and crops. It defines the characteristics of the network that will be simulated, such as the area, crop pattern and configuration of the district's conveyance infrastructure. ARD typically creates a network version for each district for each year that data is available to represent the most up-to-date version of district configuration in a given year. The Scenario Builder tool in the IDM can be used to modify an existing network version to simulate one or a combination of three types of scenarios: changes to cropping pattern, changes to irrigation methods and area expansion.

Next, the NMM configures a simulation run by opening a particular network version and then selecting the components that will be simulated. The NMM constructs a network model by connecting components from the GIS database and defining the direction of flow in each segment in the distribution network. Then, the NMM creates a time series dataset at daily time steps to store the output data during the simulation run (hourly and weekly time steps are also available). The start and end dates of canal operations are also specified in this step (typically Julian Days 127 to 280).

The base flow scaling factor (BFSF) is set next. The BFSF is a parameter in the NMM used to match the modelled return flows with measured or estimated return flows of districts (personal communication with Don Roth, ARD, July 2011). The BFSF is then the ratio between the model base flow and the required base flow to obtain the measured or estimated return flow, as explained below. The return flow in the model is assumed to be equal to,

$$Model\ Return\ Flow = Model\ Base\ Flow + X \tag{6}$$

where X equals the sum of returned downtime losses, irrigation returns from gravity systems and canal draining, calculated from NMM output. The base flow is assumed to be a characteristic of the district's operation that is independent of irrigation demands and can be calibrated. Moreover, this amount of water is needed to keep water moving in the system and to ensure that irrigation demands can always be met. To determine the BFSF use the following steps:

1. Determine the measured return flow volume for the district in a given year *(Measured Return Flow).* If a measured return flow volume is not available, use an estimate of the return flow volume. For the WID, the

estimated return flow volume is calculated as fixed percentage of the total district demand.

2. Run the NMM with a BFSF equal to 1 to calculate *Model Return Flow* and *X*.

3. Determine the model base flow *(Model Base Flow = Model Return Flow – X).*

4. Calculate the base flow required to obtain the measured return flow using *X (Required Base Flow = Measured Return Flow – X).*

5. Calculate the BFSF *(BFSF = Model Base Flow/Required Base Flow).*

6. Use the calculated BFSF for subsequent model runs.

Next, the NMM generates a database by extracting the necessary information from the Local Operating Database and creates weather files to be used by the IRM in its simulations. Once the IRM is run, the generated water demand data is imported back into the NMM. The field level demands are aggregated into demands serviced by the same conveyance work segment.

Finally, the NMM simulation is run in two phases. In the first phase, the model determines the water that will be required at each point of the network to meet the demands by using reverse time steps and working from the outlets to the inlets. In the second phase, the required water calculated in the first phase is allocated to the irrigation demands and the return flow is calculated.

The NMM accumulates total demands and return flows. Additionally, the NMM calculates the volume of water associated with canal filling and canal draining, and the total canal seepage volume based on the physical attributes of the network segments. Note that the NMM does not account for time delays associated with water travel or operational decisions of how to allocate water between different demands. In particular, the operation of reservoirs is not currently supported by the model. The NMM simply calculates the gross volume of water needed to supply all irrigation demands over a season.

3.1.3 Irrigation Requirements Module (IRM)

The Irrigation Requirement Module (IRM) simulates crop growth and on-farm irrigation water demands for over fifty crop types and forty irrigation systems (Irrigation Water Management Study Committee, 2002b). The IRM performs its calculations at four levels: Band (the portion of a Field that is irrigated in one day based on the irrigation system coverage rate), Field (a collection of bands with reference to a crop type and irrigation equipment), Block (a collection of fields with common attributes such as weather), and Project (a collection of Blocks that make up an irrigation district). The IRM runs on a daily time step and can complete single year and multiple year simulations. The module stores its data in a Microsoft Access database generated from the NMM which contains data from the Local Operating Database and output from the IRM calculations.

Irrigation water requirements in the IRM are calculated using a daily water balance approach, as illustrated in Figure 17. In the soil water balance calculations, the IRM accounts for evapotranspiration (ET_a), precipitation (P), runoff (R), net irrigation application (I), percolation losses (PL), and the water holding capacity of the soil. The soil is modelled in two layers: the root zone and the lower zone, which add up to the total soil depth (typically 1.2 m, personal communication Robert Riewe, July 2011). The root zone extends with root growth over an irrigation season and is constrained between the minimum root depth and the total soil depth. Soil moisture is added to the root zone through precipitation and irrigation applications, and subtracted through evapotranspiration and percolation into the lower zone (PL_1). The change in soil moisture in the root zone ($\Delta S_{root\ zone}$) is calculated using Equation 7

$$\Delta S_{root\ zone} = (P - R) + I - ET_a - PL_1 \tag{7}$$

Similarly, soil moisture is added to the lower zone through percolation from the root zone (PL_1), and subtracted through percolation out of the lower zone (PL_2). The change in soil moisture in the lower zone ($\Delta S_{lower\ zone}$) is calculated using Equation 8

$$\Delta S_{lower\ zone} = PL_1 - PL_2 \tag{8}$$

When the root zone grows, the soil moisture in the portion of the lower zone that became the root zone is subtracted from the lower zone moisture and added to the root zone moisture.

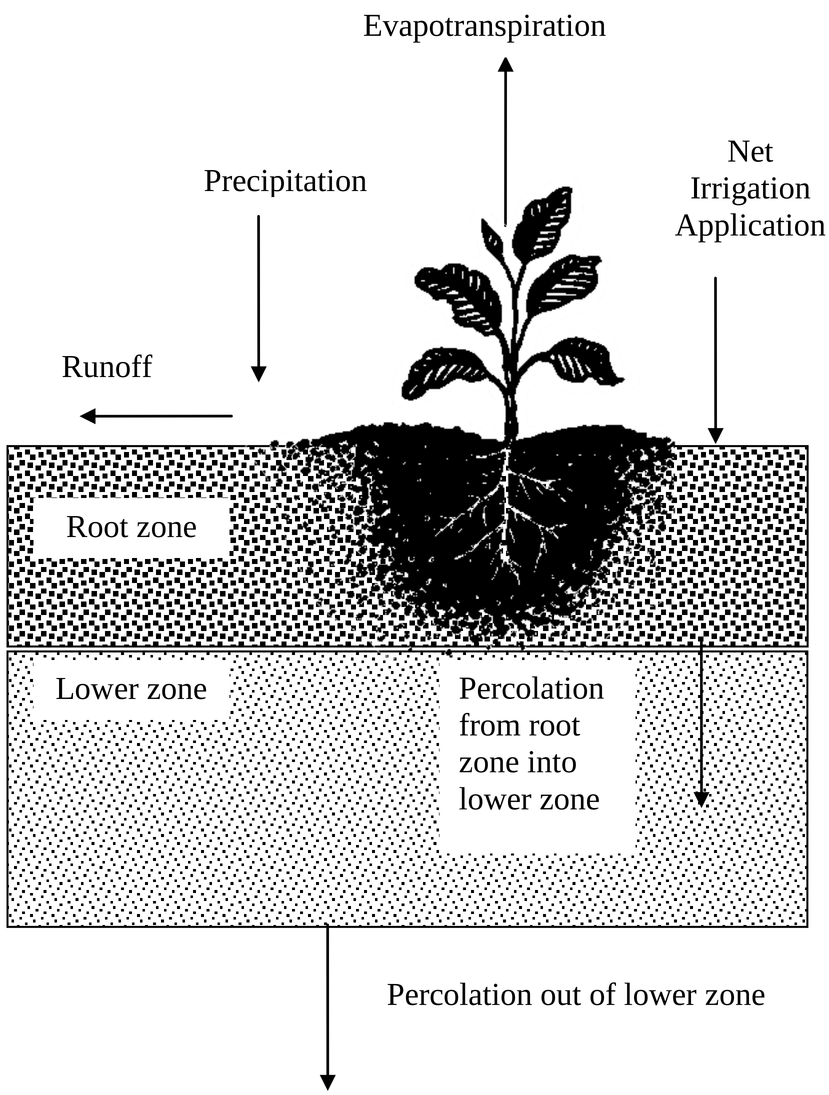


Figure 17 Soil water balance components in the IRM

The IRM calculates the daily actual evapotranspiration (ET_a) as the product of the daily potential ET, the ET Scaling Factor and the adjusted crop coefficient. The potential ET is typically taken from the value supplied in the weather dataset, but it may also be calculated from the weather data using one of three equations: Jensen-Haise, Modified Penman and Priestley-Taylor (Federer *et al.*, 1996). Note that the FAO Penman-Monteith method is broadly used as the standard method to calculate reference evapotranspiration (Allen *et al.*, 1998) but it is not included in the IRM. The ET Scaling Factor represents the percentage of evapotranspiration that is satisfied. It is set on a block by block basis and it can be modified to simulate different levels of on-farm water management. ARD uses 90% of ET for their simulations even though in reality farmers typically supply 75 to 80% (personal communication with Robert Riewe, ARD, July 2011). Irrigation experts in the province believe that 90% represents the upper limit of irrigation management expected in the future (Irrigation Water Management Study Committee, 2002a). The crop coefficient is adjusted to account for available soil moisture to decrease the actual ET when the soil moisture level is not at capacity.

The fraction of the precipitation that is added to the soil depends on runoff. Runoff is calculated using three different algorithms depending on whether the precipitation occurs during winter and whether the magnitude of the precipitation event is lesser than or greater than 25 mm in a single day, as shown in Table 2. The available model documentation does not provide details on the basis for using these equations. Note that winter lasts from the first day of the year when the maximum daily temperature is below 5°C for five consecutive days (or Julian day 1 for the first year of the simulation or Julian day 365 if the conditions are not met) until the first day when the average daily temperature has been above 5°C for five consecutive days (not sooner than Julian day 105). Again, the model documentation does not discuss the basis of these values. The difference between precipitation and runoff is added to the root zone.

Table 2 Equations used to calculate runoff in the IDM (Irrigation Water Management Study Committee, 2002b)

Condition	Equation
Winter	*Runoff = 0.177*Precipitation*
Rainfalls of more than 25 mm in a single day	*Runoff = Precipitation - [0.9177+1.811*ln(Precipitation)* [(RootZoneMoisture+LowerZoneMoisture)]/(SoilDepth*SoilMoistureCapacity)]*100]* Note: Precipitation is in inches.
Rainfalls of less than 25 mm in a single day	*Runoff = RootZoneMoisture + LowerZoneMoisture + Precipitation -1.1*(SoilDepth*SoilMoistureCapacity)* Note: The soil moisture is allowed to reach 110% of field capacity before there is any runoff. Runoff is set to zero if the equation gives a negative value

Percolation occurs when the soil moisture exceeds the soil moisture capacity. The excess soil moisture moves from the root zone to the lower zone, or leaves the lower zone as percolation loss.

An irrigation event is triggered in a field when the soil moisture in the soil, as a percentage of the soil moisture capacity, falls below the irrigation threshold specified for each crop type. The irrigation season runs from 5 days after the start of canal operations to the end of canal operations. Additional logic is used to determine whether a field should be irrigated before harvest or during the fall depending on whether the crop is a forage, silage or cereal. Irrigation events start with the first band and end with the last band of a field and they restore the soil moisture in each band to the soil moisture capacity. The number of bands in a field depends on the days that the irrigation system would take to cover the field. An irrigation event might be suspended if, after a precipitation event, the irrigation application would result in soil oversaturation.

The IRM also calculates other water volumes associated with irrigation. Downtime losses, return-flow factor (for gravity systems) and the application efficiency associated with each irrigation technology are used to calculate the daily gross irrigation applications, gross irrigation demands, irrigation returns, and irrigation losses for each field.

I. Setting up an IRM simulation

Setting up a simulation with the IRM requires a number of inputs. First, the directory of the Access database file and the weather files must be specified. Values for the soil depth, initial soil moisture fraction, ET scaling factor and the percentage of fields that can be irrigated in the fall must be given for each block. The Random Irrigation Threshold and Random Seeding Date flags can be selected to introduce variability to when fields of the same crop will be seeded and irrigated. Lastly, the years of the simulation must be defined. ARD typically adds an additional year at the beginning of the intended simulation period to ensure that the soil moisture has time to reach steady-state before the start of the simulated period (personal communication with Robert Riewe, July 2011).

3.1.4 Output Analysis

Output from the IRM and NMM is combined in a spreadsheet program to calculate annual values for the various components of a district's water balance. These values can identify district water use under different scenarios such as improvement of irrigation efficiency, changes in the type of crops grown and expansion of the irrigated area.

Losses due to reservoir evaporation and seepage, and canal evaporation are calculated manually. They are incorporated into the spreadsheet program to calculate total water demands.

The IDM can also generate files used for the Water Resources Management Model (WRMM) to determine whether river flows are sufficient to supply total irrigation demands or whether deficits are likely to occur within a given scenario (Irrigation Water Management Study Committee, 2002b).

3.1.5 Model Validation

Several studies were conducted to calibrate and verify the operation of IDM as part of the South Saskatchewan River Basin – Irrigation in the 21st Century study (Irrigation Water Management Study Committee, 2002b):

- Two studies of the IDM and the WRMM concluded that the percentage difference between measured and modelled predicted district diversion was about 5% – error fluctuations from year to year likely occurred because the IDM did not incorporate reservoir management into its calculations; while overall gross diversion errors may have been caused by incorrect establishment of base flow requirements.

- An additional validation study compared measured diversions with IDM simulated ideal district demand for four irrigation districts for conditions in1999. The total gross diversion was within ± 10% of the actual measured diversions. IDM demand followed the actual diversion through the irrigation season, but discrepancies were a result of management and operational factors (such as diversions to sustain reservoir levels or in anticipation of irrigation after forage harvest, and under-estimation of the ET scaling factor).

- IRM simulation results were also compared with field study data to check the module's ability to track soil moisture, irrigation amounts and irrigation timing. In general, the study found good correlation between modelled and recorded irrigation applications, with discrepancies caused by operator management decisions that are difficult to model.

Overall, the Irrigation Management Study Committee (2002a) concluded that the IDM represents the timing and volumes of gross irrigation demands adequately, making it a valuable tool for studying irrigation water management in southern Alberta.

3.1.6 Application of the IDM to the WID simulation scenarios

The IDM is a suitable tool for simulating irrigation water demands in Alberta, and arguably, also the alternative management scenarios established for this study of the WID. Although the model was not developed for water management – it does not currently support the operation of reservoirs, simulate dynamics of water flows in canals or simulate the effect of water stress on crop yields – it does have several characteristics that make it useful for simulating alternative irrigation management options in southern Alberta. The main advantage of the IDM is its comprehensive database of the irrigated crop characteristics, irrigation technology, conveyance infrastructure, and weather conditions that influence irrigation demands in the province's irrigation districts. The IDM can calculate quickly and effectively the water demand components for the intricate distribution of field and weather conditions that exist in an irrigation district like the WID. Additionally, the model is calibrated and validated for southern Alberta, so its water use figures are known to be reliable. Further, the IDM is the model that the government uses for irrigation planning and policy-making. Note however, that using the IDM requires a good understanding of the multiple variables, processes and assumptions involved with the model output so that the conclusions are realistic.

3.2 Rehabilitation of WID infrastructure and implementation of most efficient irrigation technologies

3.2.1 Scenario Description

The objective of this simulation scenario was to establish the difference in water use in the WID between a fully rehabilitated conveyance system and the current level of rehabilitation. A second, related simulation assessed the effects of replacing older irrigation technologies – particularly the remaining gravity and wheel move systems – with more efficient centre pivot systems. The goal was to evaluate the potential for water savings in an "ideal case" scenario.

The simulation of this scenario expanded on ARD's previous work that assessed the effects of replacing small earth laterals (clay-lined and non-lined) with pipelines, while keeping the main canals as earth canals. ARD's approach was to model rehabilitation works that were realistic, keeping in mind that there are limits to the extent that the system could be rehabilitated in practice. First, it might not be economically feasible to rehabilitate the entire system. Second, it might not be physically possible to replace certain canals sizes with pipelines and, from an operational perspective, it might be best not to convert the distribution network into a completely closed piped system s because such a system would not allow water from the open canals to spill in case of high canal discharges. In other words, certain canal segments would have to remain as open canals even if replacement with pipeline was otherwise possible. With this in mind, ARD suggested a scenario progression that used the current system as the baseline and consequently incorporated the effects of rehabilitation and a switch to more efficient irrigation technologies. Table 3 summarizes the sub-scenarios that were simulated, referred to as scenarios 1 through 4. Four complete simulation runs were conducted with the IDM using these scenarios.

Table 3 Rehabilitation Scenario Descriptions

Scenario	**Description**
1 (Baseline)	Conveyance infrastructure as of 2008
2	Conversion of small laterals into pipelines
3	Conversion of small laterals into pipelines and earth canals to clay-lined canals
4	Conversion of small laterals into pipelines,earth canals to clay-lined canals, and installation of most efficient irrigation technologies

3.2.2 Scenario set up

The simulation of the baseline was performed using a network version of the WID's conveyance infrastructure, crop mix and distribution of irrigation technologies in 2008 (even though this information was available for 2009) to take advantage of the work that ARD had already conducted which used 2008 as the baseline. This version of the distribution network represented existing infrastructure prior to the installation of the South Cluny pipeline which was done in 2009. The South Cluny Project replaced 50 km of open pipeline with closed pipeline as a result of a permanent water transfer to Rocky View County, while the South Cluny Sublaterals Project laid 18 km of PVC pipeline (Khan and Davies, 2011). The area simulated was the area actually irrigated in 2008 of 19558 ha or 48329 acres. The network versions for scenarios 2 through 4 were based on the network version for 2008 with manual changes to the construction type attribute of selected conveyance work segments in the IDM database. The seepage volume associated with the modified components was updated to reflect the change in type of construction. Table 4 shows the type of canal conversion and their associated lengths for the different scenarios. The conversions for scenario 2 represent changes from the network version used in the baseline; while the conversions for scenarios 3 and 4 represent additional changes from the network version used in scenario 2.

Table 4 Type of Canal Conversion in Rehabilitation Scenarios

Scenario	Type of Conversion	Design Discharge (m^3/s)	Length (km)
2	Earth canals to pipeline	<= 10	611
	Earth canals (clay lined) to pipeline	<=10	12
	Total		623
3,4	Earth canals lined	<=10	95
	Earth canals lined	10<Q<=20	13
	Earth canals lined	>20	31
	Total		139

For scenario 4, the IDM Scenario Builder Tool was used to create a modified network version that simulated a shift towards more efficient irrigation technologies based on the network version used for scenario 3. Less efficient technologies (gravity, hand move sprinkler, wheel move sprinkler with 2 and 4 laterals, and high pressure sprinkler pivots) were converted into low pressure sprinkler pivot by changing the equipment type associated with particular fields in the district. The benefits of replacing gravity systems are efficiency gains and the ability to use “less water to move water” because gravity systems have high irrigation returns. However, some gravity systems with well controlled water applications are already very efficient so they were left unchanged. Moreover, some gravity irrigated fields might be too small or impractical in practice to change into newer technologies even though they were considered in the simulation. Micro-drip irrigated fields also remained unchanged because they are likely used to irrigate specialty crops such as berries that would not be possible to irrigate with sprinklers. The replacement of high pressure with low pressure centre pivots is a far more common change but it is restricted by physical and financial constraints.

The NMM simulations were run with start and end dates of canal operations of Julian Day 127 and 280. The complete weather record from 1927 to 2009 was used. The base flow scaling factor (BFSF) calibration was based on the assumption that the return flow in the WID would remain at 40% regardless of the installation of closed pipelines. The BFSF, calculated using the procedure outlined in section 3.1.2, was 0.67 for the baseline and 0.979 for the system with closed pipeline laterals (scenarios 2 through 4). For most districts the base flow calibration is based on measured values of return flow; however, the calibration for the WID is based on an estimate of the district's return flow of 40% of the diversion because field measurements from return flow sites are not available. The percentage of return flow was assumed to stay the same because water needs to be kept in the system to run the pipelines at full capacity; once the water is in the system, it will be returned either through return flow sites at the end of earth canal laterals (in the baseline) or through return flow sites at the end of the main canals without closed pipeline laterals (in scenarios 2 through 4). The installation of closed pipelines does not change the volume of water that need to be kept in the canals to be able to run the system. This assumption is one of the most significant limitations of the study because it reduces the reliability of the simulation results. Using a different percentage to estimate return flow would result in differences in the total district demand.

The IRM simulations were run with an ET scaling factor of 0.9. To increase realism, The Random Irrigation Threshold, Random Seeding Date and Random Field Selection for Fall Irrigation Flags were turned on to randomize the timing of seeding and irrigation events and the selection of fields that would be irrigated during the fall. The soil was set at a depth of 1.2 m, with initial soil moisture of 50% for all the fields. Daily output was produced at the Project level only.

Output from the IRM and NMM was analyzed using ARD's spreadsheet program to determine average annual values of the district's water balance (based on 1927 to 2009 weather parameters) under the four scenarios. The different components of the water balance were used to compare the water use under the four scenarios.

3.3 Water Application Restrictions

This section describes first the method used to estimate potential yield reductions associated with water application restrictions using output from the IDM. The second part of the section describes the use of CROPWAT to validate and compare the results from the IDM and to explore alternative deficit irrigation scenarios for the WID that are not possible to simulate with the IDM.

The objective of the simulation scenarios in this section was to assess the effects of imposed total water application restrictions on crop yields and determine the distribution of seasonal demands within the irrigation season. The scenarios were prompted by the WID's plan to introduce a limit to the total water applications, which would likely start at 14 inches/acre since most irrigators actually use less than 12-14 inches/acre and then decrease over time. A limit of 8 inches/acre was recommended for simulation purposes as this was the point at which yields were expected to begin to show effects of restricted water applications (Khan and Davies, 2011).

The effect of water stress on crop yields is by far the most important factor to consider when evaluating water application restrictions, since crop development and yield can be negatively affected when full water requirements are not satisfied (Doorenbos and Kassam, 1979). Established relationships between water use and crop yields, like those described in Chapter 2, can be used to quantify the effect of different levels of water restrictions.

3.3.1 Simulations with IDM output

I. Scenario Description

The simulation in this scenario used output from the IDM and the crop yield and water requirement relationships for southern Alberta developed by Bennett and Harms (2011) to estimate yields for an optimal case where all crop requirements are met, and under various water restriction scenarios. Yield reductions, where applicable, were calculated as the percentage change between yields produced in the reference scenario and in three restriction scenarios.

II. Scenario set up

Reference scenario

Seasonal evapotranspiration and irrigation water requirements for 1989 to 2009 were calculated by running the IRM for an optimal case in which 100% of the evapotranspiration needs were supplied. The network version used to produce the IRM database represented the WID's conveyance infrastructure, crop mix, and distribution of irrigation technologies in 2009, based on the most up-to-date version of the IDM database available when the study was started in 2011. The area simulated was the area actually irrigated in 2009 of 25976 ha or 64188 acres.

The IRM was run to produce daily output at the field level. The WID network version for 2009 had 632 fields, each defined by a crop type, irrigation system type, soil type, irrigated area, randomized irrigation threshold, and randomized planting date. Two separate runs (1989-1999 and 1999-2009) were needed to ensure that the output did not exceed the allowable capacity of the Access database. The outputs for 1989 and 1999 for the first and second runs, respectively, were omitted from the analysis since these additional years at the beginning of the intended simulation period were used as model initialization – to ensure that the soil moisture levelled off before the start of the simulated period (personal communication with Robert Riewe, July 2011).

The IRM simulations were run with an ET scaling factor of 1.0 which corresponded to supplying 100% of crop water requirements, the optimal case. The irrigation season was set to run from the first week of May to the first week of October (Julian days 127-280).

Once the simulation runs were completed, data from the IRM databases were exported to individual Excel files – one for each Block and each year – for further analysis. An Access query was created to combine relevant information from the output tables in the IRM database into one table that could be easily exported to an Excel file. Individual exports for each Block and year were necessary to ensure that the allowable capacity of the receiving Excel spreadsheets was not exceeded. A macro was implemented in Access to implement the queries and reduce the processing time.

Seasonal values of evapotranspiration, precipitation and gross irrigation application for each field in the district were calculated in Excel as the sum of the corresponding daily values over the growing season. The growing season was defined from May 1 to September 30 (Julian days 121 to 273) to simplify the calculation for different crops. In the IDM, the planting date depends on the crop type and the randomization of the seeding date; a crop can be planted as early or as late as five days before or after the specified planting date of the crop when the random seeding date flag is on. The IRM calculates evapotranspiration needs for each crop starting on the planting date. However, water is available for irrigation starting on the first day of the irrigation season (Julian day 127) until the end of the irrigation season (Julian day 280), which may include irrigation after the harvest date, termed fall irrigation. Fall irrigation is a common practice used to ensure adequate soil moisture at planting in the following year. The chosen definition of the growing season simplifies the calculation of seasonal values because it avoids having to determine the specific start and end dates for each field when evapotranspiration occurs and thus permits generalized macros. It assumes that the bulk of the irrigation requirements occur in a specified period of time (May to September). This definition of the growing season has been applied in the IDM analysis spreadsheet in previous studies to calculate total seasonal available water for crops.

Crop yields were calculated with the relationships from Bennett and Harms (2011) for the crops grown in the WID (alfalfa hay, barley, barley silage, canola, corn silage, grass hay, hard spring wheat and potato). Yields for Alfalfa 2 cut and CPS wheat were calculated using the equations for alfalfa hay and hard spring wheat, respectively. Together, these ten crops account for 80% of the total irrigated area in the WID. Average (Mg/ha) and total yields for each field (Mg) were calculated using the seasonal evapotranspiration calculated from the IRM output, the respective crop yield and water requirement relationship, and the irrigated area for that crop. Average and total crop yields for the district for each crop were also calculated.

Water Restriction Scenarios

Approach

The IDM determines optimal water applications to ensure plants are not under water stress by ensuring the soil moisture is kept above the given irrigation threshold for each crop. Several efforts to simulate a water restriction scenario by modifying existing IRM parameters were investigated briefly:

1. Running the model for a portion of the season until the allowable water restriction application amount was reached. The assumption was that irrigators would take their allocated water at the beginning of the season (personal communication with Robert Riewe, July, 2011). In reality, irrigators might choose to use the allowable amount later in the season when the effect of water deficits would be greatest. However, this approach could not be simulated because the model cannot be set to run for part of the season or until a fixed amount of water is reached.

2. Running the model using a value of the ET scaling factor less than 1.0 for the entire season or for specific growing periods. This approach would represent a practice where irrigators supply less than the full evapotranspiration demands and indeed, this is typically already the case because irrigators supply between 75 to 80% of ET (personal communication with Robert Riewe, ARD, July 2011). However, this method would not result in fixed irrigation applications from one year to the next. Furthermore, it is not possible to change parameters in the middle of a simulation to represent different levels of irrigation during the different growing stages – instead, any value chosen for the scaling factor remains constant for the duration of a simulation.

3. Modifying the irrigation threshold for the crops so that the soil moisture was allowed to fall below the specified threshold before an irrigation

event. This method would delay irrigation applications but it would not result in a fixed amount of irrigation application.

Consequently, the selected approach fixed the seasonal gross irrigation application, instead of using the IDM to estimate it, and then calculated the resulting yields using the seasonal precipitation observed for 1989 to 2009. Note that the IDM was not used to perform irrigation calculations; only data from the IDM database was used. Three water restriction levels were defined at 8, 6 and 4 inches/acre (corresponding to 502, 377 and 251 mm/ha). These restrictions are relatively strict – and a 4 inch/acre restriction is particularly strict – but they are consistent with a shift towards reduced water consumption by the irrigation sector (Khan and Davies, 2011). Other districts have set their water application limits at levels that have no effect on yields: the Bow River and Lethbridge Northern Irrigation Districts set theirs at 24 and 17 inches, respectively (personal communication Robert Riewe, December 2011). In the simulation, the gross irrigation application, or the volume of water that is required for irrigation including irrigation efficiency losses, was fixed at each of the restriction levels. This is the volume of water that leaves the district's infrastructure; therefore, it could be easily metered if the restriction was put in place. A similar approach is used in simulations with the FFIRM where the total irrigation water available at the farm level (as calculated by the WRMM model) is used as the maximum total irrigation water that can be used and yields are calculated based on a seasonal evapotranspiration value that is the sum of the net irrigation application and the available precipitation (Irrigation Water Management Study Committee, 2002c). No such work has been conducted previously at the district level.

The fixed gross irrigation application was compared with the average gross irrigation application in the reference scenario to determine the percentage of the gross irrigation water application needs that would be supplied under a restriction scenario for each crop type.

Finally, the total water available for evapotranspiration was assumed to be the sum of the net irrigation application (gross irrigation application adjusted for the irrigation system efficiency) and the observed precipitation for the particular field. Average yields (Mg/ha) were calculated using this resulting seasonal evapotranspiration value for each water restriction scenario. Average yields for the restriction scenarios were compared to yields in the reference scenario to estimate yield reductions.

Limitations

The first limitation with this approach is that all fields received a fixed volume of water, regardless of their actual requirements. If the fixed gross irrigation application in a restriction scenario exceeded the reference gross irrigation application, the yield from the reference scenario was used. This situation arose most commonly for crops that require relatively small amounts of seasonal irrigation, such as barley.

A second limitation was that the stored soil moisture depletion, which would normally be included as part of the seasonal evapotranspiration value, was not available from the model output so it was not considered as part of the field water supply available to the plant. Additionally, the observed precipitation in the WID was higher than the values used by Bennett and Harms (2011) – 250mm for perennial forage and root crops and 150mm for annual crops – for effective growing season precipitation plus stored soil moisture depletion. This implies that the stored soil moisture depletion is likely small compared to the precipitation and irrigation applications and can be neglected in our first-order estimates. The FFIRM model also ignored the contribution of the stored soil moisture in the calculation of the seasonal evapotranspiration (Irrigation Water Management Study Committee, 2002c).

Finally, a third limitation was that the evaluation of the effect of limited water supply on individual growth periods was not attempted because the values of the yield response factor, ky, for specific growth stages are not actually known for the region. Further, in practice, crops that are more valuable and sensitive to water stress would be prioritized to maximize crop yields at the expense of lower value or more water resistant crops. However, as this study was intended as a sensitivity analysis of the effects of water restrictions on crop yields, it was assumed that every crop would receive all the irrigation water it requires up to the fixed gross irrigation application amount. Thus, the response of individual crops was evaluated, rather than the effect of allocating water to one crop at the expense of another.

3.3.2 Simulations with CROPWAT

CROPWAT, introduced in previous sections, is a well known irrigation management decision support tool developed by the FAO (Smith, 1992). The program takes climatic data as input and combines it with crop coefficients for each growing stage to calculate crop water requirements following the procedures outlined in Allen *et al.* (1998). The model includes a number of options for the timing and amount of irrigation applications that allow the evaluation of different irrigation scheduling options. Irrigation events can be scheduled following actual dates provided by the user, assuming no restrictions in the availability of water, using fixed intervals to represent a rotational system, or whenever a specified level of depletion in the root zone is reached. The user can indicate application depths or specify the percentage of the soil capacity to which the soil is to be refilled with irrigation. Detailed documentation for the model is available (Smith, 1992; FAO, 2012b).

The objective of using CROPWAT in this research was to compare the results from the IDM simulations with a well tested and widely used model. A disadvantage of using CROPWAT is that the model is best suited for single year and single field simulations. CROPWAT does not support multi-field simulations of more than 20 fields so it was impractical to simulate all of the 632 fields in the

WID. Therefore, simulations for representative combinations of crops, soil and irrigation system efficiency in the district were run. The scenarios explored in CROPWAT were mostly exploratory in nature. The goal was to investigate the differences and similarities between the two models, as well as the potential for using CROPWAT for scenarios that the IDM cannot handle.

CROPWAT 8.0 software available for public use from the FAO was used for this portion of the research (downloaded from http://www.fao.org/nr/water/infores_databases_CROPWAT.html on May 3, 2012).

This section describes the differences in the calculation procedures between the IDM and CROPWAT and explains the methodology followed to set up simulation runs in CROPWAT using available data from the IDM database. Since the modelling procedures differ between the two models, some of the IDM data had to be adapted to fit the requirements of CROPWAT. Smith and Kivumbi (2002) used a similar approach when they calibrated the main crop parameters in CROPWAT (by adjusting the K_c values, critical depletion factor and k_y values) to match measured water applications and yield responses to water stresses from experimental data.

I. Weather Data (Climate/ET$_o$ and Rain)

Daily values of potential evapotranspiration (mm) and precipitation (mm) from the IDM weather files were used as input to CROPWAT. CROPWAT stores daily evapotranspiration and rain data in different files for each year and location (station) (FAO, 2012b). Therefore, the data were input into separate CROPWAT files for each IDM block for 2009.

CROPWAT includes five methods for calculating the effective rainfall: Fixed percentage, Dependable rain (FAO/AGLW formula), Empirical formula, USDA Soil Conservation Service, and effective rainfall equal to zero (FAO, 2012b).The recommended *Fixed percentage option at 80%* was used (FAO, 2012b).

II. Crop Data

CROPWAT requires crop data to run a simulation – the program has pre-defined crop data for several common crops taken from FAO publications, including some crops that are grown in the WID (alfalfa, barley, corn, grass, potato and wheat) (FAO, 2012b). However, the crop data in the IDM database represent the characteristics of crops grown in southern Alberta more closely than the standardized crop data in CROPWAT. Printouts of the crop data used in CROPWAT after modifications to match the characteristics of southern Alberta can be found in Appendix A.

Crop Coefficient Curves

CROPWAT uses a linear piece-wise function to define the daily crop coefficient, K_c, needed to calculate actual crop evapotranspiration from potential evapotranspiration following Equation 1. CROPWAT defines the crop coefficient curve as linear segments for four growth stages (initial, development, mid-season and late season) by joining three K_c values (FAO, 2012b) as shown in Figure 18. In contrast, in the IDM database, daily crop coefficient values for different crops are given for Julian days 105 to 288 based on observed experimental data (see Figure 16).

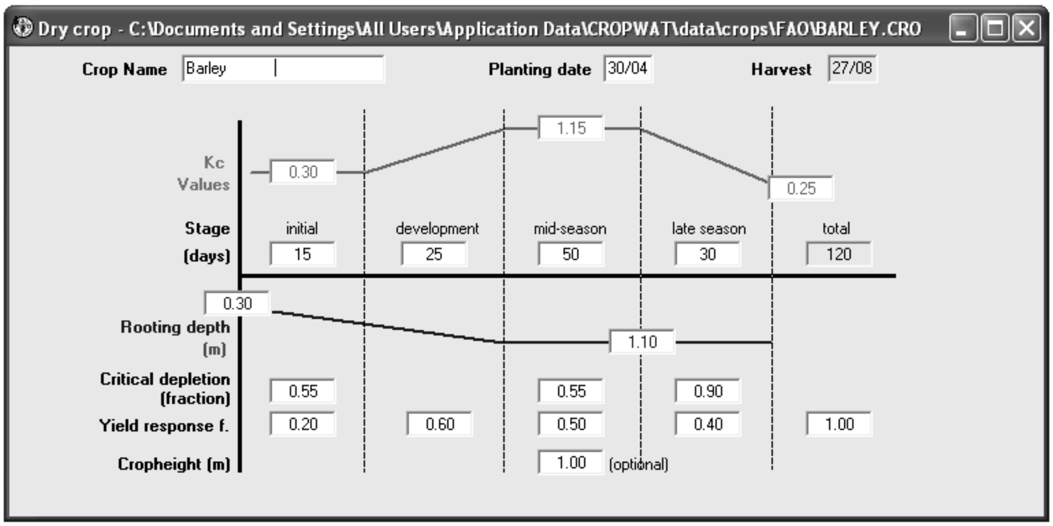


Figure 18 Screen capture of crop module data input in CROPWAT 8.0 (example data from pre-defined crop data for barley)

In order to replicate the crop data in the IDM database, crop coefficient curves for CROPWAT were created by fitting linear segments to the IDM crop coefficients curves as shown in Figure 19 for barley. The values of K_c at the three growth stages and the lengths of the growth stages were modified manually until the linear function resembled the IDM curve. The curve matching exercise used the following criteria:

1. The planting and cut date (first and last day when the crop coefficient is not zero) in the IDM database were matched as closely as possible. The harvest date in CROPWAT did not always match the harvest date in the IDM as a result of the matching exercise.

2. The steepness of the curves was fitted as closely as possible.

3. The area above and below the linear segments and the IDM curve was kept roughly the same. Often, the IDM curve was above or below the CROPWAT curve during the mid-season.

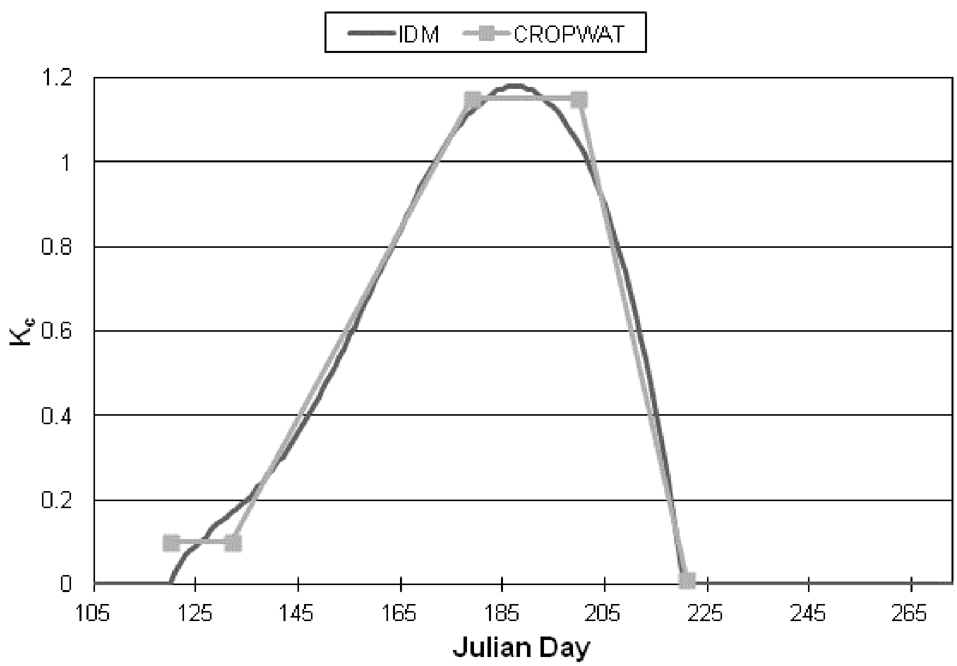


Figure 19 Crop coefficient curves for barley in the IDM and CROPWAT

In the IDM, crop coefficient curves for crops that are harvested more than once during the growing season (for example alfalfa 2 cut, tame pasture and lawn turf) show sharp drops at the cutting dates. The simulation of the entire season of such crops cannot be conducted using CROPWAT's linear crop coefficient curves because only one harvest date is allowed per year.

Rooting Depth

CROPWAT simulates linear root growth starting from the minimum rooting depth at the day of planting to the maximum rooting depth at the first day of the mid-season (FAO, 2012b), as seen in Figure 18. The minimum and maximum root depths for each crop given in the IDM crop dataset were used as input for CROPWAT.

Critical depletion

CROPWAT defines three different values for the "critical depletion", the fraction of the soil moisture that will trigger an irrigation application, depending on the development stage (FAO, 2012b) as seen in Figure 18. In the IDM, the corresponding value is the "irrigation threshold" that characterizes the level at which a crop will be irrigated. The same "irrigation threshold" parameter from the IDM database for each crop was used for all three critical depletion values in CROPWAT.

Yield response factor

CROPWAT requires the yield response factor, k_y, for the entire season and during each crop growth stage to estimate the effect of water stress on crop yields (FAO, 2012b) as seen in Figure 18. Yield response factors for selected crops for the entire season were available from Bennett and Harms (2011), so they were used for the entire season. If CROPWAT had pre-defined data for a crop, then the yield response factors for the individual growth stages were used to estimate the yield reductions over the different crop growth stages.

III. Soil data

Three soil files were created in CROPWAT to match the three soil types defined in the IDM database – fine, medium, and coarse – which differ based on their soil moisture capacity. The total available soil moisture was set to the 210, 180 and 120 mm per meter, for fine, medium, and coarse soil, respectively. Since the IDM does not use an infiltration rate in its calculations, the maximum rain infiltration rate (mm/day) in CROPWAT was set to 30 mm/day as specified in the pre-defined soil types (FAO, 2012b). The maximum rooting depth was set to 120 cm based on the soil depth used in the IDM.

The initial soil moisture depletion (as a percentage of the total available moisture) in CROPWAT was initially set to 0.50 to coincide with the initial soil moisture fraction used in the IRM for the first day of the simulation period (usually the first day of the year). However, this value caused an irrigation event on the day of planting that did not occur in the IRM simulations because the soil moisture is usually close to full capacity by the time of planting is approached due to winter precipitation. An initial soil moisture depletion of 0% was used instead.

IV. Irrigation scheduling

One of the biggest advantages of CROPWAT compared to the IDM is the model's ability to simulate different irrigation scheduling options. In the IDM, an irrigation event is triggered in a field when the soil moisture falls below the specified irrigation threshold for the crop and the soil is always refilled to soil moisture capacity – thus the timing and amount of the irrigation events cannot be defined by the user. In CROPWAT, several irrigation schedules are possible by combining the timing and application options in Table 5.

Table 5 Scheduling criteria in CROPWAT 8.0 (FAO, 2012b)

Irrigation timing

- Irrigate at user defined intervals
- Irrigate at critical depletion (100% critical depletion)
- Irrigate below or above critical depletion
- Irrigate at fixed interval per stage
- Irrigate at fixed depletion
- Irrigate at given ET crop reduction per stage
- Irrigate at given yield reduction
- No irrigation (rainfed)

Irrigation application

- User defined application depth
- Refill soil to field capacity
- Refill soil below/above field capacity
- Fixed application depth

The scheduling options do not include an option for a fixed maximum irrigation application amount like that needed to simulate a water restriction scenario for WID. Instead, three sets of simulation scenarios were selected to be simulated with CROPWAT for the WID to explore the model's application to the particular circumstances of the district:

1. Optimum irrigation applications. The purpose of this scenario was to compare the optimum irrigation schedules calculated with the IDM and CROPWAT and thus to ensure compatibility of results between the models. Irrigation events were set to occur at 100% critical depletion and the application was set to refill to 100% of field capacity. When comparing the optimal irrigation schedules calculated by IDM to CROPWAT for a specific field, the irrigation system efficiency of that field was used.

2. Fixed irrigation amounts evenly distributed over a number of irrigation events with no irrigation during the initial stage and late season. The objective was to simulate a water restriction scenario of 4 inches/acre (251 mm/ha) as closely as possible with CROPWAT. There are two ways to set a fixed amount of gross irrigation water in CROPWAT: user defined application depths and fixed application depths. Fixed intervals per stage combined with an appropriate user defined application depth were selected to simulate a total gross irrigation application of roughly 250 mm over the season, equivalent to the 4 inches/acre water restriction scenario. The

weighted average of the irrigation efficiency throughout the district of 78% was used to simulate a representative field in the district. Medium soil was used as it is the most common soil in the WID.

3. Deficit irrigation by imposing water stress throughout the growing season. Ideally for a simulation of deficit irrigation in the WID, the crops would be subjected to water stress during one or more growth stages, but CROPWAT's option to irrigate below or above critical depletion does not allow for the value of the allowable depletion to be specified for each growth stage. Therefore, the options to irrigate below critical depletion (at different percentages of the critical depletion) and to refill the soil to field capacity were selected. This procedure is similar to that used by Smith *et al.* (2002) introduced in section 2.4.2. Again, the weighted average of the irrigation efficiency throughout the district of 78% and medium soil were used to simulate a representative field in the district.

4 Results and Discussion

This chapter discusses the simulation results and their implications. Section 4.1 presents the results for the full rehabilitation and implementation of most efficient irrigation technologies scenario. The results in this section compare water use at the farm, conveyance system and district levels, as well as the water use efficiency for the four rehabilitation scenarios described in Section 3.2. Section 4.2 discusses the results for the water application restrictions scenario. Results from the simulations with IDM output are presented first, followed by results from the simulations with CROPWAT.

4.1 Rehabilitation of WID infrastructure and implementation of most efficient irrigation technologies

Water is divided into different components as it makes its way through the WID's conveyance network. Figure 20 shows a graphical representation of the water balance components calculated from IDM output for the baseline scenario and the weather conditions in 2008 as an example. A considerable portion of the district's water diversion is used to supply crop water requirements at the farm-level (net irrigation application, 39%). Water is lost through on-farm losses (sprinkler evaporation, 11%), reservoir losses (seepage and evaporation, 1.4%) and canal losses (seepage and evaporation, 14%). A small percentage of the water diverted (0.6%) may remain in the conveyance system after the irrigation season. Lastly, a substantial amount of the water (34%) returns to a receiving water body downstream, either through return flow sites at the end of the conveyance system (base flow, canal draining and downtime losses), or as accumulated runoff and percolation from fields irrigated with gravity systems. Understanding the water allocation between the different uses is important when analyzing the effects of the different rehabilitation scenarios and calculating water efficiency (Burt *et al.*, 1997). This section compares the water balance components for rehabilitation scenarios 1 through 4 (see Table 3) at the farm, network system and district level. The values are averages of the annual district water balance components as calculated by the IDM for 1927 to 2009 weather conditions. Refer to Section 3.2.2 for scenario descriptions and assumptions.

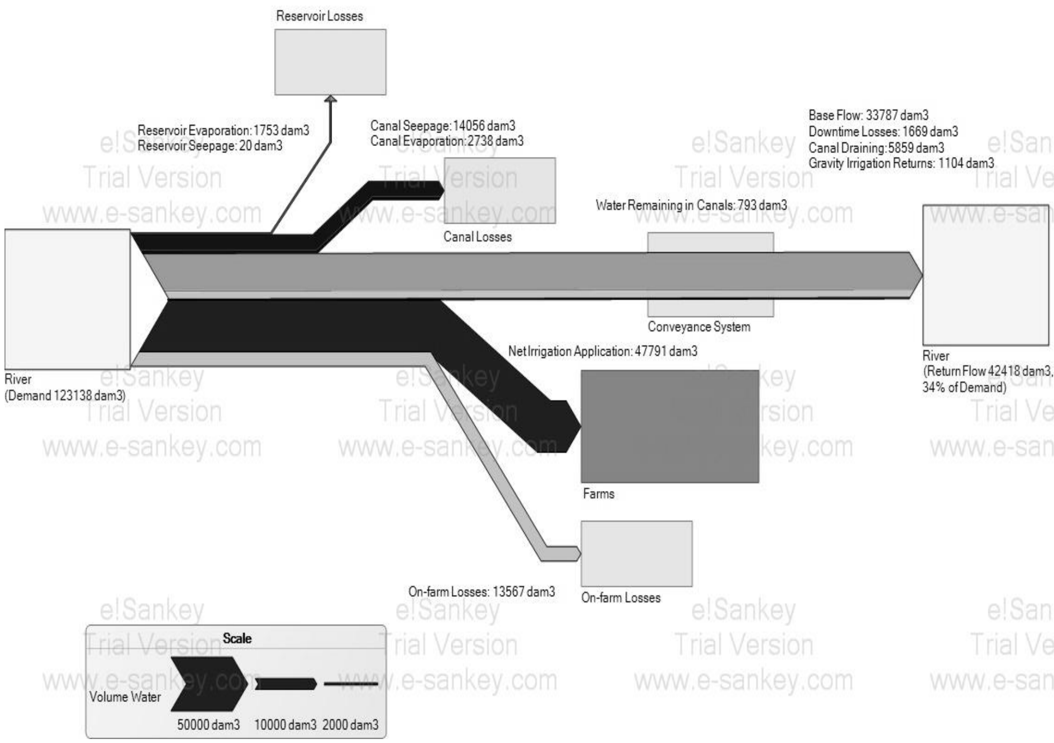


Figure 20 Water balance components in the WID for baseline scenario for year 2008

4.1.1 Farm Level Water Use

The results in this section refer to water use at the farm, rather than district level. Water use at this level is a function of crop water requirements and the irrigation systems efficiency.

I. Net Irrigation Application

The net irrigation application (or the amount of moisture added to the soil) did not change with rehabilitation or implementation of most efficient technologies (roughly 41,160 dam^3), as was expected, because scenarios 1 through 4 were based on optimal irrigation requirements which depend only on weather conditions (Figure 21). Note that small differences between the calculated net irrigation applications in the different scenarios did exist and were caused by the randomization of seeding times and irrigation thresholds; this caused slightly different net irrigation application volumes each time the IRM module was run.

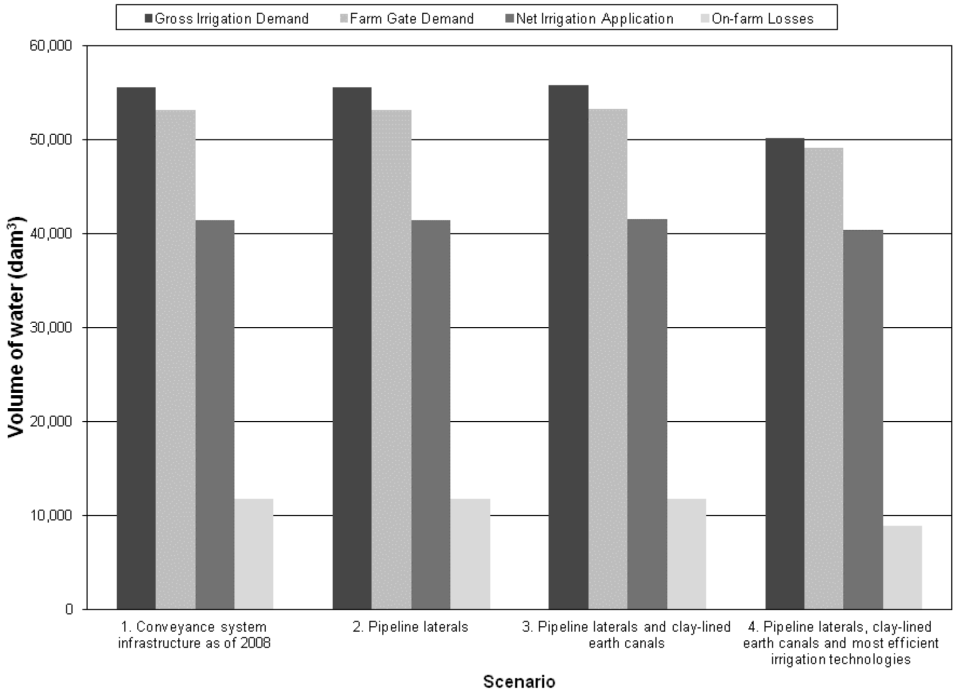


Figure 21 Gross irrigation demand, farm gate demand, net irrigation application, and on-farm losses for rehabilitation and implementation of most efficient irrigation technologies

II. On-farm Losses

The farm gate demand (net irrigation application plus on-farm evaporation losses) did not decrease for scenario 2 – conversion of small laterals into pipelines – and 3 – conversion of small laterals into pipelines and earth canals to clay-lined canals – compared to the baseline (average of 53,200 dam^3) (Figure 21). However, the installation of most efficient technologies (scenario 4) decreased the farm gate demand by 7% to 49,200 dam^3 due to a 25% reduction in on-farm losses (sprinkler evaporation losses) (Figure 21). These water savings were caused by conversion of less-efficient hand move, wheel move, and high pressure sprinkler pivots with application efficiencies ranging between 73-76%, to low pressure sprinklers with application efficiencies of 82%.

III. Gross Irrigation Demand

At the farm level the gross irrigation demand (water demand at the farm turnout including downtime losses and irrigation returns from gravity) also decreased with the installation of most efficient technologies from about 55,600 dam^3 in the baseline to 50,200 dam^3 in scenario 4 (a 10% reduction) (Figure 21). These water savings were partly caused by the replacement of gravity systems with return flow factors between 0.27 and 0.45, with sprinklers that have no associated return flows. Irrigation returns decreased from 923 dam^3 in the baseline to 0 dam^3 in scenario 4. Additional water savings (500 dam^3 from the baseline to scenario 4) occurred due to the replacement of hand move and wheel move systems that have high downtime losses (between 80 to 130 minutes/day), with sprinklers that have lower downtime losses (between 30 to 40 minutes/day).

4.1.2 Conveyance Network Level Water Use

Water use at this level is a function of the physical characteristics of the conveyance infrastructure that determine system losses. Rehabilitation decreased canal seepage and canal evaporation losses from 14,056 and 2,503 dam^3 in the baseline to 5,356 and 1,582 dam^3 in the fully rehabilitated scenario by decreasing the seepage and evaporation rates of the canal segments that were lined or replaced by pipelines (Figure 22). The installation of pipeline laterals reduced canal seepage by 38% compared to the baseline, while the additional lining of earth canals reduced the seepage losses by 62% compared to the baseline. Canal evaporation decreased by 37% with the installation of pipeline laterals.

These water savings are substantial considering that the canal losses represented about 14% of the total district demand in the baseline. However, the extent of rehabilitation modelled might be limited by financial and physical constraints (such as size of the field, type of crop irrigated, and cost, availability and suitability of construction materials). Rehabilitation is expensive. Lined main canals cost $550,000/km, while unlined main canals cost $600,000/km; and pipeline including installation costs $775.00 for 48” pipe, $375.00 for 36” and $170.00 for 24” per meter (Khan and Davies, 2011).

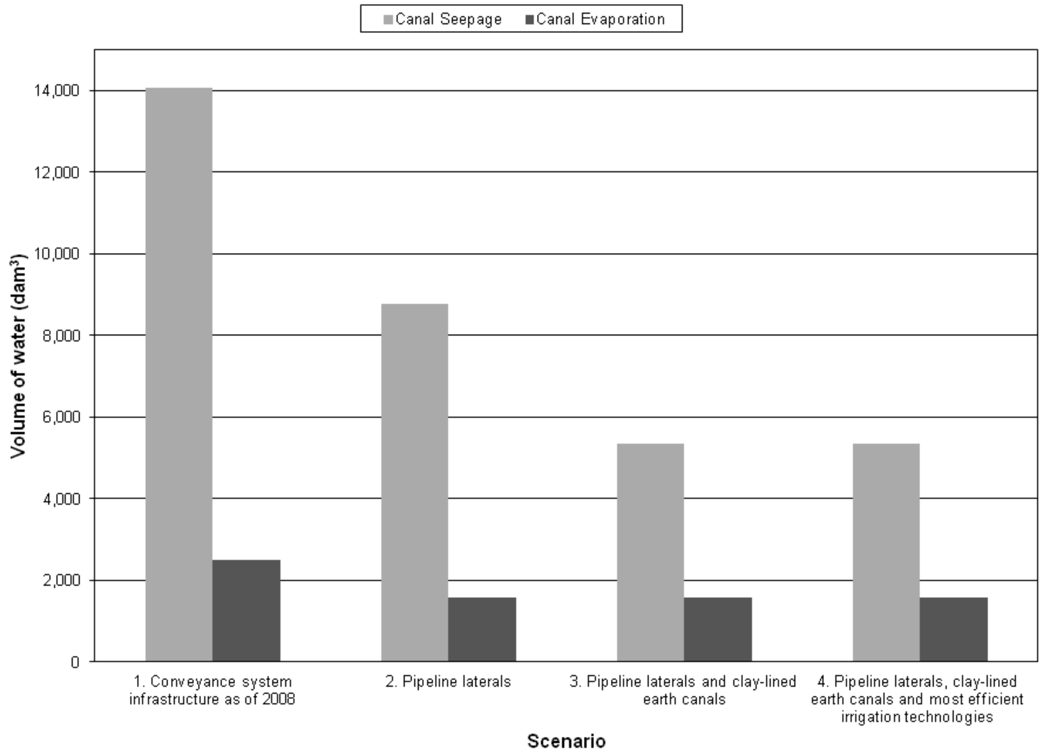


Figure 22 Canal losses for rehabilitation and implementation of most efficient irrigation technologies

4.1.3 District Level Water Use

The results in this section refer to water use at the district level. Water use is a function of crop water requirements and irrigation systems efficiency at the farm level, as well as of the system losses at the conveyance network level.

I. Total Consumptive Use

The total consumptive use is the total water diverted by the district minus any water that returns to the river. Rehabilitation and implementation of most efficient technologies reduced the total consumptive use through reduction of on-farm and system losses (Figure 23). The installation of pipelines decreased the consumptive use by 9% compared to the baseline, while the additional lining of earth canals decreased the consumptive further by 13% compared to the baseline because of fewer seepage and evaporation losses. The implementation of most efficient technologies reduced the total consumptive use by 19% from the baseline by decreasing the gross irrigation demand at the farm level.

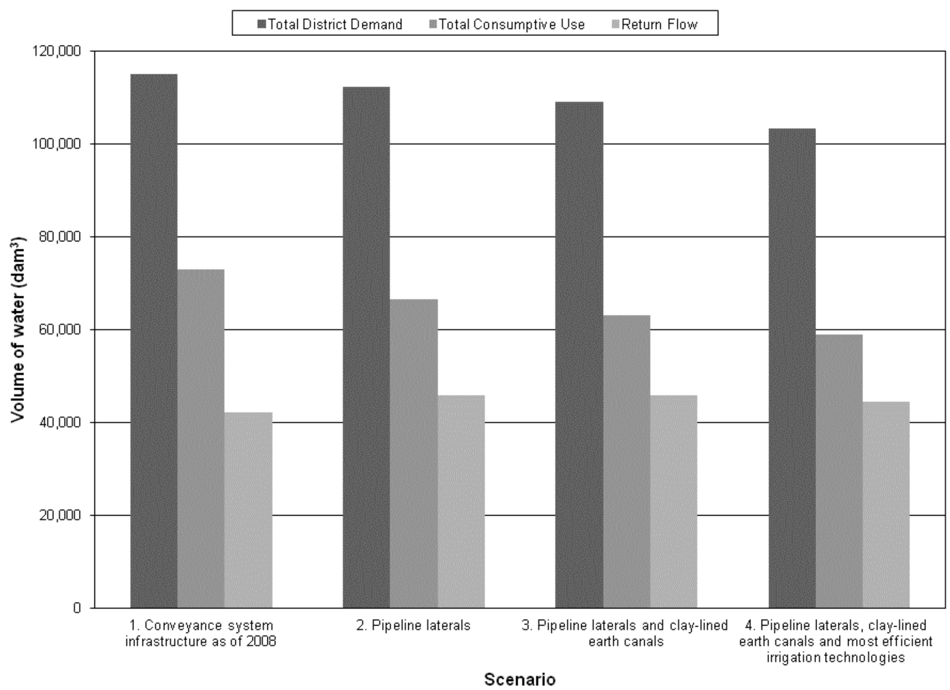


Figure 23 Total district demand, total consumptive use and return flow for rehabilitation and implementation of most efficient irrigation technologies

II. Return Flow

The fraction of the return flow to the total district demand was roughly 40% for the four scenarios (37%, 41%, 42% and 43% for scenarios 1 to 4, respectively)

(Figure 23). Recall that the base flow scaling factor used in the simulation runs for scenarios 2 to 4 was calculated with the assumption that the return flow would remain at 40% regardless of the installation of closed pipelines. The idea was that the installation of closed pipelines would not change the amount of water that needs to be kept in the canal system to run the pipelines at full capacity. Excess water is needed in the system to ensure that irrigation demands at the most eastern parts of the district can be supplied in a timely manner. In scenarios 2 through 4, water that returned from the ends of open canals in the baseline would return to the river together with the remaining return flow through spillways at the end of main canals, since the open canals would be replaced with closed pipelines.

The assumption that the return flow fraction would remain constant is one of the most significant limitations of the study. First, the lack of measured return flows for the WID means that the return flow fraction must be assumed even for the conveyance network that is currently in place. Second, since the IDM is not an operational model that calculates real-time water flows through the conveyance system, a more detailed analysis of how the installation of closed pipelines would change the operation of the conveyance system is not possible.

III. Total District Demand

The total district demand includes all water consumed to satisfy crop water requirements, system, on-farm and reservoir losses, and return flows – it is the volume of water that the district would need to divert at the head works. From scenario 1 to 4, the total demand for the WID decreased with rehabilitation and implementation of most efficient irrigation technologies from about 115,000 dam^3 in the baseline to about 103,000 dam^3 in the completely modernized scenario (Figure 23). This represents a 10% reduction in water demand for the "ideal case" scenario. The demand decreased with each level of rehabilitation and implementation of most efficient technologies because less water was lost either through system or on-farm losses. Scenario 2 reduced the total district demand by 2% from the baseline, while scenario 3 and 4 reduced the demand by 5% and 10%, respectively. Recall, however, that previous model validation studies discussed in section 3.1.5 determined that the total gross diversion calculated with the IDM was within ± 10% of the actual measured diversions. Therefore, the differences in total district demand between the scenarios may not be significant.

4.1.4 Water Use Efficiency

Water use efficiency in the four rehabilitation scenarios varies depending on the definition used, but in general, it increased with more intense levels of district modernization (Table 6). On-farm efficiency, calculated as the percentage of net irrigation application to the farm gate demand, increased from 78% to 82% with the implementation of most efficient technologies. Project total irrigation efficiency, calculated as the percentage of farm gate demand to the total irrigation demand, also increased with rehabilitation from 46% in the baseline to a maximum of 49% in scenario 3. The project total efficiency represents the efficiency with which the conveyance system supplies water to the farm gate as a percentage of the diversion at the head works. The implementation of most efficient technologies reduced the farm gate demand in scenario 3 compared to scenario 4, thus the lower project total efficiency. Similarly, the irrigation efficiency (1), calculated as the volume of water stored in the root zone (net irrigation application) as a percentage of the total water released at the project head works (total irrigation demand) (Doorenbos and Kassam, 1979) increased from 36% to 39% with rehabilitation and implementation of most efficient technologies. If the water that is returned to the river is considered so that the net withdrawal as opposed to the gross withdrawal is used – as suggested by Jensen (2007) – the irrigation efficiency (2), calculated as the ratio of net irrigation application to total consumptive use, increased from 57% to 68% with rehabilitation and implementation of most efficient technologies.

Table 6 shows that different definitions of irrigation efficiency can lead to different assessments of the WID's performance. So far on-farm efficiency has been the main indicator of the performance of the irrigation sector in Alberta. On-farm efficiency values are high for the WID even at current levels of district modernization (78%) because they reflect the widespread use of high efficiency irrigation technologies. The "ideal case" scenario simulated here would not increase on-farm efficiency significantly. The other three definitions of efficiency generate much lower values – 36 to 57% for the baseline depending on the definition used. However, these indicators incorporate technical as well as managerial aspects that determine the way the WID operates, so they provide a more complete picture of the district's operations. For example, the low efficiency values reflect the large base flow needed to ensure irrigation demands are satisfied as a result of lack of reservoir storage and long travel times. The rehabilitation scenarios explored here would not increase project total efficiency or irrigation efficiency according to Doorenbos and Kassam (1979) significantly (a maximum of 3% increase). However, irrigation efficiency according to definition (2) would increase by 11% from the baseline to scenario 4. Nonetheless, indicators such as this one should be used with caution because the return flows may or may not always be reused as they might not always return to the same river system. Additionally, given the limitations of the IDM, the small differences in water use efficiency between the scenarios may not be significant.

Table 6 Water use efficiency calculated using different definitions for rehabilitation and implementation of most efficient irrigation technologies scenarios

Scenario	On-farm efficiency	Project total efficiency	Irrigation efficiency (1)	Irrigation efficiency (2)
1 (Baseline)	78%	46%	36%	57%
2	78%	47%	37%	62%
3	78%	49%	38%	66%
4	82%	48%	39%	68%

4.2 Water Application Restrictions

This section discusses the effects of imposed total water application restrictions in the WID on crop yields. Simulation results obtained for three restriction levels with IDM output are presented first, followed by simulation results for exploratory scenarios investigated with CROPWAT.

4.2.1 Simulations with IDM output

Three water restriction levels (8, 6 and 4 inches/acre) were studied using IDM output and the crop yield and water requirement relationships by Bennett and Harms (2011) – refer to section 3.3.1 for scenario descriptions and assumptions. This section discusses first crop yields under optimum irrigation applications, then water demand shortfalls under the restriction scenarios, and finally expected yield reductions under the restriction scenarios.

I. Yields in the reference scenario

Simulated crop yields per hectare for the WID under optimum irrigation applications varied with weather conditions for 1990 to 2009 (Figure 24). The values represent the average yields of all the fields throughout the district where a certain crop was grown. Crops with high yield per hectare (for example, potato) appear to fluctuate more than crops with low yields per hectare (for example, canola). However, this fluctuation is actually a result of the relative values of evapotranspiration and yield that the crop yield and water relationships are based on – in general, crop yields varied within ± 14% from the average from year to year over the simulation period for a given crop type (Table 7). Crop yields per hectare were less than the reported maximum potential yield for the region because the WID experiences lower heat unit values due to its northern location relative to other irrigation districts. This situation results in ET_a values that are lower than ET_m reported by Bennett and Harms (2011) even at optimum irrigation applications. Note that the trends in Figure 24 vary between different crops because the results are averages of yields throughout the WID, and the crop mix and weather parameters vary between different blocks in the district.

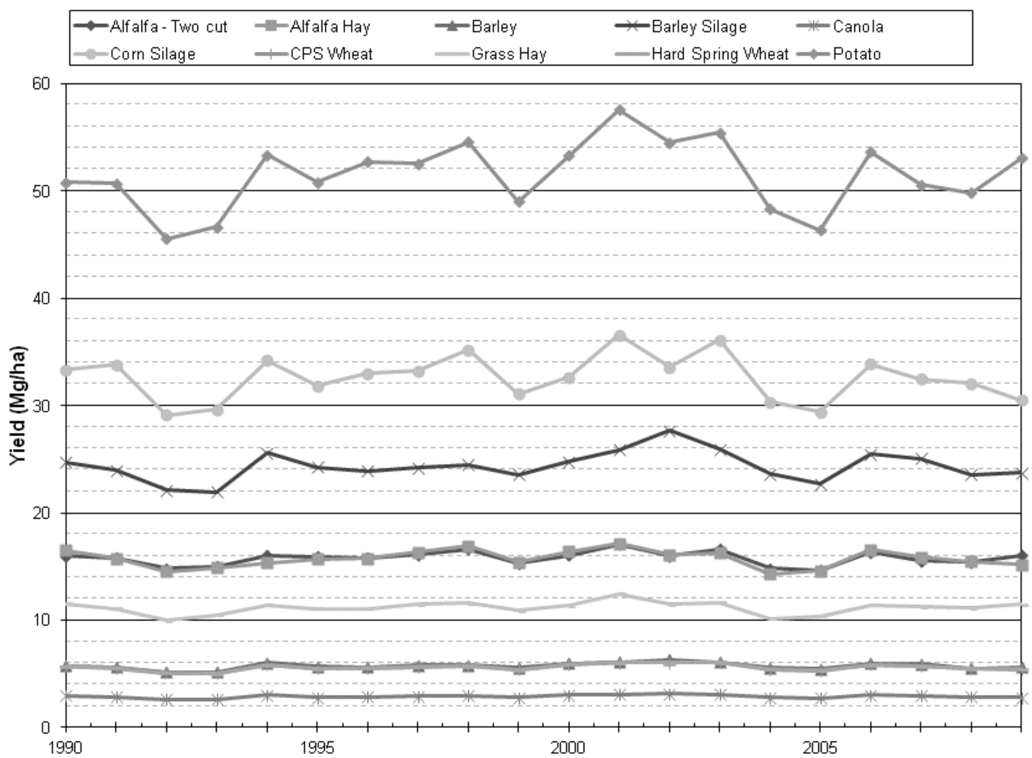


Figure 24 Simulated average yield per area for ten crops in the WID for the reference scenario for 1990 to 2009

Table 7 Minimum, maximum and average simulated yields for ten crops in the WID under optimum irrigation applications compared to maximum potential yields for the region.

Crop	Minimum Yield (Mg/ha)	Maximum Yield (Mg/ha)	Average Yield (Mg/ha)	Maximum Potential Yield * (Mg/ha)
Alfalfa - Two cut	14.6	17.1	15.8	18
Alfalfa Hay	14.3	17.1	15.7	18
Barley	5.2	6.3	5.7	7.3
Barley Silage	22.0	27.6	24.3	31.4
Canola	2.6	3.1	2.9	3.9
Corn Silage	29.1	36.6	32.5	44.8
CPS Wheat	5.1	6.1	5.6	7.8
Grass Hay	10.0	12.5	11.2	13.4
Hard Spring Wheat	5.0	6.1	5.6	7.8
Potato	45.6	57.6	51.3	67.2

*Based on reported values in Bennett and Harms (2011).

Calculated yields for all crops were lowest in 1992, 1993, 2004 and 2005, and highest in 2001, 2002 and 2003 (Figure 24). These differences in yields correspond to differences in potential evapotranspiration – for example, low levels of evapotranspiration in 1992, 1993, 2004, and 2005 resulted in low yields. Crop evapotranspiration is a function of crop type climatic factors, such as solar radiation, relative humidity, and temperature (Allen *et al.*, 1998).

Figure 25 shows that the precipitation varied temporally and spatially within the district for the simulated period. The precipitation throughout the district was lowest in 2001 and highest in 2005. Blocks, or collections of fields with common weather parameters, are shown in the figure for comparison. As an example, Block A is located in the West of the district, while Block E is located to the East. For a given year, the difference in precipitation between different blocks ranged from 14 to 120 mm per irrigation season.

In the hot, dry years of 2001, 2002, and 2003, available precipitation did not limit crop yields because irrigation water was used to compensate for the difference between potential evapotranspiration and precipitation. These results stress the importance of irrigation, especially for crops with high evapotranspiration demands (alfalfa, for example) and in years of low precipitation. In 2001, the potential evapotranspiration was high and high yields were possible even though the precipitation was low because irrigation supplied enough water to ensure that the optimum crop requirements were met. On the contrary, 2005 had low levels of potential evapotranspiration which lead to low yields, even though the precipitation was high, which meant less irrigation water was needed.

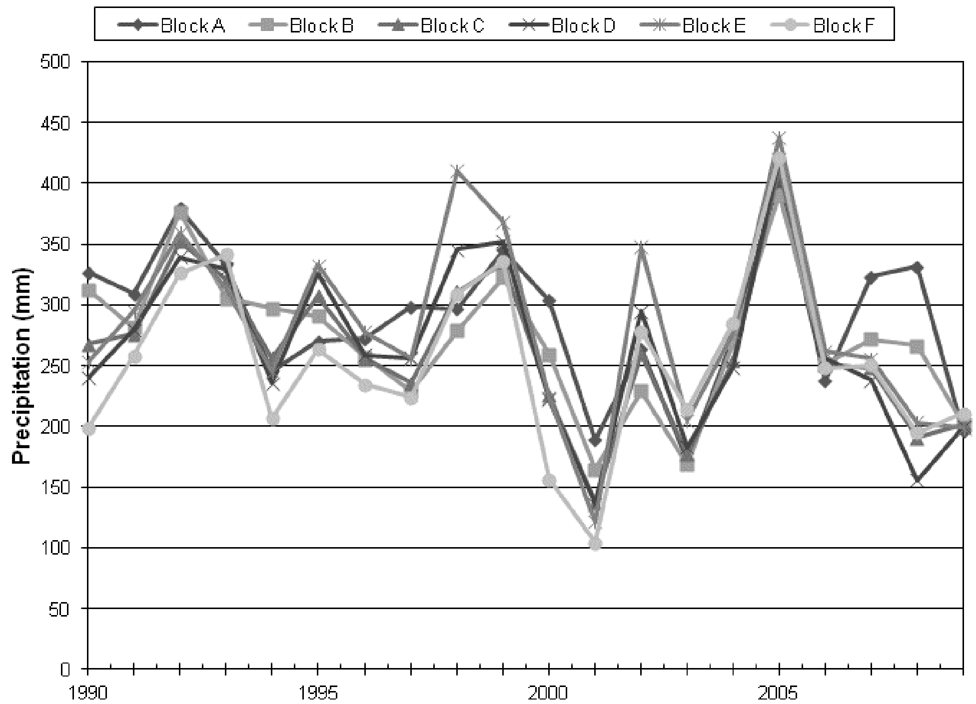


Figure 25 Precipitation in the six agro-climatic regions in the WID for 1990-2009

Average total yearly estimates of crop yields for the WID based on 1990 to 2009 weather conditions are shown in Figure 26 (yields for alfalfa hay and grass hay were excluded from this graph because they are too small compared to the rest of the crops; yields were 191 and 413 Mg, respectively). Error bars show the maximum and minimum yields for the simulation period. Note that the total yield is a function of both crop area (Figure 7) and the maximum potential yield per hectare, which ranges from 3.9 Mg/ha for canola to 67.2 Mg/ha for potatoes (Bennett and Harms, 2011). Total alfalfa yields were significantly higher than for other crops because of the large percentage of the irrigated area that is dedicated to alfalfa in the WID.

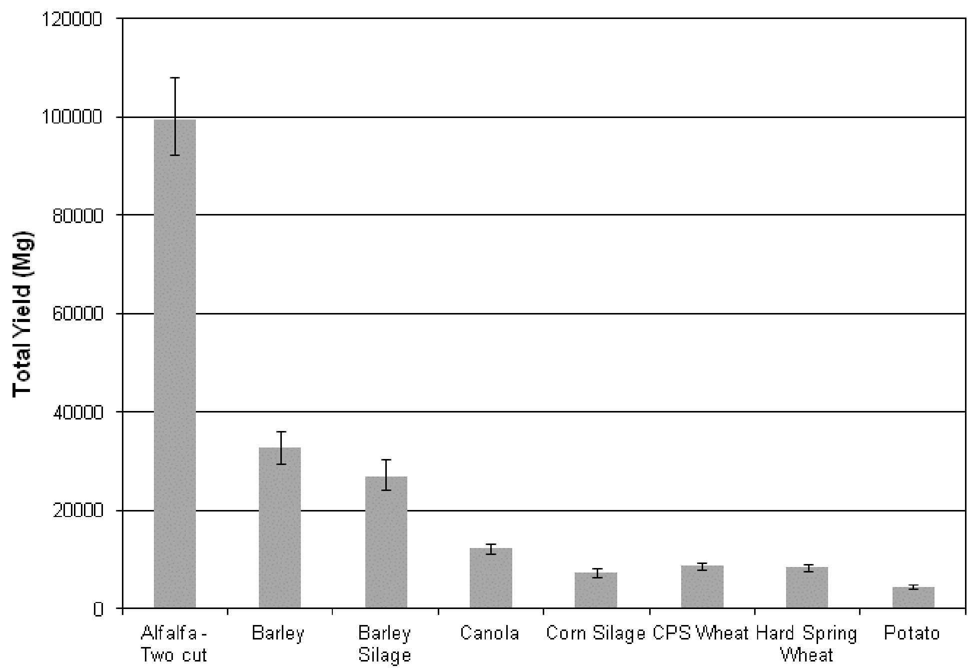


Figure 26 Average total yields for the WID based on 1990 to 2009 weather conditions

II. Satisfying Irrigation Demands

The results discussed here compare water demand for optimal yields with the water that would be available under the three water restriction levels to calculate water shortfalls under imposed restrictions.

Table 8 shows the gross irrigation application calculated by the IDM for optimum irrigation in the reference scenario for 1990 to 2009 weather conditions. Table 9-11 on the following pages show the percentage of the average gross irrigation application that would be satisfied under water restrictions of 8, 6 and 4 inches/acre (which correspond to 502, 377 and 251 mm/ha) by crop type. The values are presented with the following colour convention for easier analysis:

- Blank: with water restriction, supply is more than 100% of what is needed
- Green: with water restriction, supply is 80 to 100% of what is needed
- Yellow: with water restriction, supply is 70 to 80% of what is needed
- Orange: with water restriction, supply is 60 to 70% of what is needed
- Red: with water restriction, supply is less than 60% of what is needed

Note that the gross irrigation application calculated by the IDM includes irrigation that occurs after harvest, termed fall irrigation. Crops in the IDM may be irrigated after harvest depending on whether fall irrigation is enabled for a field, the random selection of fields that are fall irrigated and the percentage of fields that are allowed to be irrigated in the fall. Fall irrigation does not contribute directly to crop growth because evapotranspiration after harvest is zero. However, it was included in the gross irrigation demand because it is a common practice and it forms a considerable percentage of the seasonal irrigation water requirements of a field.

An 8 inch/acre (502mm/ha) water restriction would satisfy optimum irrigation needs for most crops (Table 9). Market gardens would suffer most, followed by alfalfa and native pasture. Note that market gardens are a special case. Their irrigated area is small (only one field of 20 hectares) and it is irrigated using an undeveloped gravity system with low efficiency (60%) and high return flow factor (0.45) which explains the small percentage of the gross irrigation application that would be supplied even at a lenient water restriction level. Alfalfa and native pasture would be supplied with more than 80% of the gross irrigation application in most years, except in years of low precipitation and high evapotranspiration such as 1994, 2000, 2001, 2003, 2006, 2008, and 2009, when between 60 to 80% of the gross irrigation application would be supplied. Note that the irrigated area of native pasture and alfalfa hay is also small (one field each of 20 and 12 ha, respectively); whereas alfalfa 2-cut is the most widely grown crop in the district (170 fields with a total area of 6330 ha).

Table 8 Gross irrigation applications under optimum irrigation applications

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa 2 Cut	608	553	397	449	635	521	587	575	555	437	656	804	587	632	494	410	630	554	665	663
Alfalfa Hay	532	492	394	394	551	519	591	591	591	512	591	834	689	591	492	492	591	499	584	591
Barley	210	188	84	107	261	178	234	227	145	106	278	318	296	288	188	144	209	215	256	285
Barley Silage	174	158	80	97	211	145	201	202	131	80	248	306	300	288	171	127	208	209	241	260
Canola	236	228	101	123	290	186	239	259	174	135	310	346	316	312	206	166	245	255	280	306
Corn Silage	243	249	121	88	274	148	258	236	249	195	330	441	290	337	195	155	297	249	329	259
Cps Wheat	303	280	142	188	349	239	276	312	192	184	379	422	349	354	263	214	280	300	346	346
Dry Peas	235	181	103	103	255	176	250	238	154	131	331	367	345	279	195	169	219	229	303	294
Durum Wheat	337	303	168	168	396	270	337	362	236	236	371	472	371	421	303	236	303	371	404	371
Flax	270	303	93	168	362	202	244	244	168	177	371	404	303	345	168	202	312	270	362	345
Grain Corn	159	223	127	104	175	199	263	255	247	175	263	374	279	342	151	143	303	223	239	255
Grass Hay	263	269	124	145	313	257	393	287	317	181	328	493	419	381	228	236	348	269	307	439
Green Feed	136	149	90	90	210	130	166	190	113	64	204	261	283	269	141	117	190	184	193	245
Hard Spring Wheat	295	279	138	181	337	236	285	305	195	173	382	410	360	342	263	213	278	300	351	348
Market Gardens	1207	1409	805	805	1811	1409	1409	1207	805	1006	1409	1610	1811	2012	1207	1409	1811	1610	1207	1610
Native Pasture	604	604	201	335	604	201	604	537	402	402	604	805	604	604	604	402	604	402	805	604
Nursery	263	241	131	176	341	245	287	280	176	141	343	375	314	360	252	234	279	265	287	334
Oats	234	235	75	146	244	171	245	255	128	139	305	325	249	232	188	185	211	234	292	287
Oats Silage	185	123	62	93	216	123	185	185	93	62	240	202	240	164	177	154	185	185	231	247
Potato	224	297	198	193	364	321	396	338	323	231	318	455	363	428	234	260	394	320	313	421
Rye	303	337	168	168	371	270	320	371	236	236	371	371	404	337	270	202	236	270	337	337
Tame Pasture	255	223	101	125	307	155	252	201	272	51	303	432	235	251	131	158	257	179	315	303
Turf Sod	183	197	116	118	171	109	189	228	231	179	182	266	207	191	195	168	247	179	207	245

Table 9 Percentage of the average gross irrigation demand that would be supplied under a water restriction of 8 inches/acre (502 mm/ha)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa 2 Cut	83%	91%			79%	96%	86%	87%	91%		77%	62%	86%	79%			80%	91%	76%	76%
Alfalfa Hay	94%				91%	97%	85%	85%	85%	98%	85%	60%	73%	85%			85%		86%	85%
Barley																				
Barley Silage																				
Canola																				
Corn Silage																				
Cps Wheat																				
Dry Peas																				
Durum Wheat																				
Flax																				
Grain Corn																				
Grass Hay																				
Green Feed																				
Hard Spring Wheat																				
Market Gardens	42%	36%	62%	62%	28%	36%	36%	42%	62%	50%	36%	31%	28%	25%	42%	36%	28%	31%	42%	31%
Native Pasture	83%	83%			83%		83%	94%			83%	62%	83%	83%	83%		83%		62%	83%
Nursery																				
Oats																				
Oats Silage																				
Potato																				
Rye																				
Tame Pasture																				
Turf Sod																				

Table 10 Percentage of the average gross irrigation demand that would be supplied under a water restriction of 6 inches/acre (377 mm/ha)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa 2 Cut	62%	68%	95%	84%	59%	72%	64%	65%	68%	86%	57%	47%	64%	60%	76%	92%	60%	68%	57%	57%
Alfalfa Hay	71%	76%	96%	96%	68%	73%	64%	64%	64%	74%	64%	45%	55%	64%	76%	76%	64%	75%	64%	64%
Barley																				
Barley Silage																				
Canola																				
Corn Silage												85%								
Cps Wheat											99%	89%								
Dry Peas																				
Durum Wheat					95%							80%		89%					93%	
Flax												93%								
Grain Corn																				
Grass Hay							96%					76%	90%	99%						86%
Green Feed																				
Hard Spring Wheat											99%	92%								
Market Gardens	31%	27%	47%	47%	21%	27%	27%	31%	47%	37%	27%	23%	21%	19%	31%	27%	21%	23%	31%	23%
Native Pasture	62%	62%			62%		62%	70%	94%	94%	62%	47%	62%	62%	62%	94%	62%	94%	47%	62%
Nursery																				
Oats																				
Oats Silage																				
Potato							95%					83%		88%			96%			90%
Rye													93%							
Tame Pasture												87%								
Turf Sod																				

Table 11 Percentage of the average gross irrigation demand that would be supplied under a water restriction of 4 inches/acre (251 mm/ha)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa 2 Cut	41%	45%	63%	56%	40%	48%	43%	44%	45%	57%	38%	31%	43%	40%	51%	61%	40%	45%	38%	38%
Alfalfa Hay	47%	51%	64%	64%	46%	48%	42%	42%	42%	49%	42%	30%	36%	42%	51%	51%	42%	50%	43%	42%
Barley					96%						90%	79%	85%	87%					98%	88%
Barley Silage												82%	84%	87%						97%
Canola					87%			97%			81%	73%	79%	81%				98%	90%	82%
Corn Silage					92%		97%				76%	57%	87%	75%			85%		76%	97%
Cps Wheat	83%	90%			72%		91%	80%			66%	60%	72%	71%	95%		90%	84%	73%	73%
Dry Peas					99%						76%	68%	73%	90%					83%	85%
Durum Wheat	75%	83%			63%	93%	75%	69%			68%	53%	68%	60%	83%		83%	68%	62%	68%
Flax	93%	83%			69%						68%	62%	83%	73%			81%	93%	69%	73%
Grain Corn							96%	99%			96%	67%	90%	73%			83%			99%
Grass Hay	95%	93%			80%	98%	64%	87%	79%		77%	51%	60%	66%			72%	93%	82%	57%
Green Feed												96%	89%	93%						
Hard Spring Wheat	85%	90%			75%		88%	82%			66%	61%	70%	73%	96%		90%	84%	72%	72%
Market Gardens	21%	18%	31%	31%	14%	18%	18%	21%	31%	25%	18%	16%	14%	12%	21%	18%	14%	16%	21%	16%
Native Pasture	42%	42%		75%	42%		42%	47%	62%	62%	42%	31%	42%	42%	42%	62%	42%	62%	31%	42%
Nursery	96%				74%		88%	90%			73%	67%	80%	70%			90%	95%	88%	75%
Oats								98%			82%	77%							86%	87%
Oats Silage																				
Potato		84%			69%	78%	63%	74%	78%		79%	55%	69%	59%			64%	79%	80%	60%
Rye	83%	75%			68%	93%	78%	68%			68%	68%	62%	75%	93%			93%	75%	75%
Tame Pasture	99%				82%		99%		92%		83%	58%					98%		80%	83%
Turf Sod												94%								

A 6 inch/acre (377mm/ha) water restriction would still satisfy irrigation needs for most crops (Table 10). However, alfalfa and native pasture would be affected in most years, not only dry years. Alfalfa 2 cut would receive as low as 50% of its requirements in dry years, between 60 to 80% in normal years, and above 80% in wet years because more precipitation would be available to provide additional moisture.

A 4 inch/acre (251 mm/ha) water restriction would result in an irrigation deficit for most crops (Table 11). Nevertheless, the shortage would not be severe for the majority of crops, including common crops such as barley, barley silage, canola, CPS wheat, hard spring wheat, tame pasture and turf sod, which would receive between 70% and 100% of their gross irrigation application requirements, depending on the crop type and the weather conditions of each year. Further, a 4 inch/acre restriction would supply potato, durum wheat, flax and grass hay with 60% to 100% of their requirements, depending on the year. In contrast, alfalfa, market gardens and native pasture would only be supplied with, at maximum, 50% of their requirements – a level that would severely hinder production of these crops, as discussed in the next section titled Yield Reductions. A 4 inch/acre (251 mm/ha) water restriction would limit crop production for the majority of crops in dry years such as 1994, 2000, 2001, 2002, 2003, 2008, and 2009.

III. Yield reductions

Under water application restrictions, the water shortfalls discussed in the previous section would lead to yield reductions. Yields decreased with increasing levels of water restriction. Table 12 - 14 show estimates of average yield reductions under the three water restriction levels for 1990 to 2009 weather conditions for the ten crops for which crop yield and water relationships were available. The values presented here are estimates of average yield reductions and should be evaluated qualitatively only. Yield reductions varied yearly depending on the weather conditions – yield reductions were highest for 2001, the driest year in the simulated period. In reality, yields in the WID under water restrictions would be affected by a variety of other factors, including crop management practices.

Table 12 Estimates of yield reductions under water restriction of 8 inches/acre (502 mm/ha)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa - Two cut	-7%	-3%			-8%	-2%	-5%	-8%	-3%		-12%	-29%	-4%	-19%	-1%		-8%	-4%	-11%	-14%
Alfalfa Hay	-2%	-2%					-6%	-13%	-9%		-9%	-27%	-12%	-23%			-11%	-4%	-3%	-12%
Barley																				
Barley Silage																				
Canola																				
Corn Silage																				
CPS Wheat												-1%								
Grass Hay																				
Hard Spring Wheat												-1%								
Potato																				

Table 13 Estimates of yield reductions under water restriction of 6 inches/acre (377 mm/ha)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa - Two cut	-21%	-16%	-2%	-4%	-23%	-13%	-19%	-23%	-13%	-4%	-26%	-43%	-16%	-34%	-13%		-23%	-18%	-26%	-29%
Alfalfa Hay	-16%	-17%		-8%	-12%	-15%	-21%	-28%	-23%	-8%	-23%	-41%	-27%	-37%	-10%		-25%	-19%	-18%	-27%
Barley																				
Barley Silage																				
Canola												-1%								
Corn Silage												-11%								
CPS Wheat											-1%	-8%								
Grass Hay												-11%		-5%						
Hard Spring Wheat											-1%	-9%		-1%						
Potato												-7%		-7%						

Table 14 Estimates of yield reductions under water restriction of 4 inches/acre (251 mm/ha)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alfalfa - Two cut	-36%	-31%	-14%	-20%	-38%	-28%	-35%	-38%	-27%	-18%	-41%	-57%	-31%	-48%	-29%	-3%	-38%	-34%	-41%	-44%
Alfalfa Hay	-30%	-32%	-10%	-24%	-27%	-30%	-35%	-42%	-37%	-23%	-38%	-54%	-41%	-51%	-27%	-8%	-40%	-34%	-33%	-42%
Barley											-2%	-14%		-2%						
Barley Silage												-3%								
Canola											-4%	-22%		-7%					-1%	
Corn Silage								-2%			-3%	-38%		-26%					-12%	-4%
CPS Wheat	-5%				-4%		-1%	-2%			-12%	-34%	-1%	-17%			-1%	-1%	-9%	-4%
Grass Hay					-2%		-2%	-9%	-3%		-4%	-30%	-9%	-26%			-7%	-2%	-1%	-18%
Hard Spring Wheat	-4%				-4%		-1%	-2%			-12%	-34%	-2%	-17%			-1%	-1%	-8%	-4%
Potato					-10%		-2%		-1%			-28%	-7%	-29%			-12%			-21%

Water restrictions had the highest effect on alfalfa yields at the three levels studied because of alfalfa's high irrigation water requirements. The average potential reduction for alfalfa was 7%, 17% and 32% in the 8, 6 and 4 inch/acre water restriction scenarios, respectively. As would be expected, yield reductions for alfalfa were significantly higher for hot and dry years (for example, 2001), and for individual fields with less efficient irrigation systems.

Yield reductions for crops other than alfalfa in the 8 and 6 inch/acre scenarios were small, but could reach 10% for corn silage, CPS wheat, grass hay, hard spring wheat, and potato in the 6 inch/acre scenario for a dry year such as 2001.

On average, crop yields for most crops in the 4 inch/acre water restriction were reduced, with the highest yield reductions for alfalfa, followed by corn silage, wheat, grass and potato (average reductions of 5%), and minimal reductions for barley, barley silage and canola (average reductions of less than 2%). However, yield reductions for dry years were significantly higher. For example, barley and canola, which suffered minimal or no yield reductions in most years, experienced yield reductions of 14% and 22 % for the 2011 simulation scenario. Note that these figures represent the average yield reduction in the district; individual fields could have higher or lower yield reductions depending on the location of the field and the irrigation system efficiency.

Tame pasture and turf sod are widely grown in the WID. Even though specific relationships were not determined for these two crops because the maximum yield and evapotranspiration are not known, the relative change in yield would be similar to grass (hay) because the yield response factor, k_y, is expected to be of similar magnitude (personal communication with Rod Bennett, March 21, 2012).

IV. Discussion of simulation assumptions and limitations

The yields in the water restriction scenarios were calculated assuming that the evapotranspiration was the sum of precipitation and a fixed gross irrigation application adjusted for the irrigation system efficiency in a particular field. In other words, the plant was assumed to use as much water as was available from precipitation and net irrigation application up to the value of the irrigation application restriction. Yields in the water restriction scenarios were then compared to yields in the reference scenario to calculate potential yield reductions. However, close examination of the IRM output for the reference scenario revealed that the evapotranspiration did not equal the sum of net irrigation application and precipitation, as was assumed for the water restriction scenarios. The seasonal net application calculated by the IRM was often higher than the difference between the seasonal evapotranspiration and precipitation. This was caused by two reasons: the way the model determines irrigation applications and the inclusion of fall irrigation in the net irrigation application. Table 15 shows an example of this situation for a field of barley – values represent seasonal sums as defined in the methodology.

Table 15 Parameters used for the calculation of yield reductions in the 4 inch/acre water restriction for a field of barley

Reference scenario		
Precipitation	IRM output	257 mm
Gross irrigation application	IRM output	330 mm
Irrigation efficiency	IRM output	76%
Net irrigation application	IRM output	251 mm
Fall irrigation application	IRM output	75 mm
Evapotranspiration	IRM output	354 mm
“Excess” irrigation	Calculated	154 mm
application	Calculated	5.6 Mg/ha
Yield per hectare		
Water restriction scenario		
Precipitation	IRM output	257 mm
Gross irrigation application	Fixed	251 mm
Irrigation efficiency	IRM output	76%
Net irrigation application	Calculated	197 mm
Evapotranspiration	Calculated	448 mm
Yield per hectare	Calculated	7.4 Mg/ha

In the reference scenario, the seasonal net irrigation application calculated by the model (251 mm) was higher than the difference between seasonal evapotranspiration and precipitation (354 mm – 257 mm = 97 mm). In a way, the model irrigated “more” than was needed for the season (an “excess” of 154 mm). However, there are good reasons for the “over-application” and the behaviour is realistic. First, a portion of the net irrigation application (75 mm) occurred during the fall when the evapotranspiration needs are zero as discussed earlier. Second, the additional discrepancy is attributed to the procedure used to determine irrigation applications in the IRM. The model does not simply look at the difference between the total seasonal evapotranspiration and the total seasonal precipitation to determine the total seasonal irrigation application. Instead, the model keeps a daily water balance which triggers an irrigation event whenever the soil moisture drops below the allowable threshold. The seasonal net irrigation application could be high especially if precipitation occurs in few episodes of heavy rain with long periods of dry conditions. Heavy precipitation will generate runoff and percolation so that not all of the precipitation can be stored in the soil and used by the plant; while dry conditions will prompt irrigation events to ensure crops are well watered. The model has no way of predicting if a precipitation event will happen in the near future. Therefore, it will irrigate whenever the crop needs it even if the deficit could be satisfied in the following days with rainfall. In reality, some irrigators might use a similar approach to water their crops, while others might look at the weather forecast and decide to wait for a rainfall event within the next few days depending on the level of risk they are willing to take.

This situation has implications for the yield reduction estimates calculated here. For the barley example in Table 15, the net irrigation application in the water restriction (197 mm) was lower than in the reference scenario (251 mm). Since only a percentage of this field's requirements would be supplied, a lower yield in the restriction scenario compared to the reference scenario would be expected. However, in the restriction scenario the evapotranspiration (448 mm) calculated as the sum of the precipitation (257 mm) and the fixed gross irrigation application adjusted by the irrigation efficiency (251 mm * 76% = 197 mm), was higher than in the reference scenario (354 mm) and would lead to a higher yield (7.4 Mg/ha) than in the reference scenario (5.6 Mg/ha). The yield of the reference scenario was used instead, and no yield reduction was calculated, because higher yields than those calculated under optimum irrigation are unrealistic. If the evapotranspiration had resulted in a lower yield in the water restriction than in the reference scenario, then that yield would have been used and a yield reduction would have been calculated. In summary, the main assumption in the calculation of yields under water restrictions is that all of the net irrigation application contributes to evapotranspiration. In the reference scenario, only a portion of the net irrigation application contributes to evapotranspiration.

Close examination of the IRM output also revealed small discrepancies in the IRM's water balance that are worth mentioning. The soil moisture calculation procedures seemed to differ slightly from the procedures outlined in the model's documentation. Specifically, the soil moisture in a sample field decreased even when there was no evapotranspiration or percolation into the lower zone. Evaporation from the soil is a possible explanation since the discrepancies occurred in spring and fall time when the earth is relatively bare. However, the model does not calculate evaporation outside of the crop evapotranspiration (personal communication, Robert Riewe, February, 2012). Cumulative differences in the root zone moisture for a sample field of barley were about 50 mm per year. These differences affect the estimates of gross irrigation applications because lower root zone moisture levels could lead to additional irrigation applications.

In reality, several additional factors need to be considered to assess the potential impact of water applications limits. These include operational implications, farm management factors, economic factors, and the effect of water stress on different growth stages.

Under a water restriction scenario, water demands at the farm level are lowered, leading to potential water savings. However, conveyance system losses do not necessarily decrease because the evaporation and seepage rates in the canals remain relatively constant – they are a function of the physical characteristics of the canals and pipelines, not only of the volume of water in them. Since the conveyance system in the WID has long travel times from the upstream reservoirs, water volumes in the canals at any point during the irrigation season are likely to remain high even for a water restriction scenario to ensure adequate water supply for farms in the distant, eastern part of the district. As discussed for the rehabilitation scenario, the volume of water needed to “move” water through the WID conveyance system – the base flow – would remain unchanged, so the system would behave very similarly in terms of losses under a water restriction scenario compared to the reference scenario (personal communication Robert Riewe, ARD, July 2011). Ideally, estimates of total irrigation demand for the district would have been calculated for the water restriction scenarios. However, it was not possible to run the NMM for the water restriction scenarios because the model requires daily irrigation application amounts for each field and the restriction scenarios used a seasonal gross irrigation application amount.

Additionally, under reduced water supply, irrigators might modify their management decisions. First, they might be inclined to choose to grow only those crops that require less irrigation, or to prioritize crops that are more valuable and sensitive to water stress at the expense of others. Labbé *et al.* (2000) modelled irrigation management strategies at farm level during water shortages when irrigation was partially restricted. Even though their approach did not involve a maximum allowable irrigation application, but rather times during the irrigation season when irrigation was not allowed, their conclusions might apply to the WID under water restrictions. Specifically, Labbé *et al.* (2000) determined that irrigation bans quickly lead to water stress events and that irrigators might modify their irrigation operations as a result. Four irrigation scheduling adaptations during water shortages were identified: (1) extending the length of an irrigation event and delaying the irrigation of one or more portions of a field (better for short duration restrictions and good soils); (2) using the equipment more intensively by applying more water on irrigation days to avoid delaying the irrigation schedule and water stress; (3) reducing the irrigation depth in all fields and for fields with deep soil (rarely implemented as it requires adjustment to the irrigation equipment); and (4) skipping fields or portions of the field with good soil storage capacity or later in the season once the period of highest stress sensitivity is over. Options 1, 3 and 4 could lead to some water savings. Option 2 does not lead to water savings; instead, it transfers the demand to the authorized days. However, this adaptation is expected when faced with temporary irrigation bans. The impact of water restrictions on irrigator behaviour is not possible to simulate with existing tools like the IDM.

Further, crops are more sensitive to water stress during certain growth stages and skilled irrigators would prioritize irrigation during these stages to ensure maximum yield. The estimates of yield reductions presented here cannot capture the effects of such practices, because of the capabilities of the IDM and the lack of yield response factors for specific growth stages.

Lastly, further economic analysis to investigate the tradeoffs between different levels of irrigation for the various crops in the WID is needed to support the results presented here. Such estimates would provide a better estimate of the financial implications of imposing water restriction scenarios.

4.2.2 Simulations with CROPWAT

This section discusses the results from exploratory simulations with CROPWAT. Refer to section 3.3.2 for detailed descriptions of the three scenarios explored: optimal irrigation applications, fixed applications of roughly 250 mm over the season and deficit irrigation by imposing water stress throughout the growing season.

I. Optimal irrigation application

The first set of simulations with CROPWAT was intended to compare optimal irrigation schedules as calculated by the IDM and CROPWAT. Figure 27 and

Figure 28 show the optimal net irrigation applications for fields of barley and wheat as calculated by the two models. The IDM results show IRM output for a field of barley located in Block A with fine soil and a sprinkler pivot high pressure irrigation system with application efficiency of 76%, and a field of hard spring wheat in Block D with medium soil and a sprinkler pivot low pressure irrigation system with application efficiency of 82%. The IRM was run for 2008 and 2009, but only results for 2009 were used to ensure that the soil moisture stabilized during the first year of the simulation. The CROPWAT results show simulation output using weather data for Block A and Block D for 2009, crop data and soil data modified from IDM data as described in section 3.1, and an irrigation system efficiency of 76% and 82%, for barley and hard spring wheat respectively. Irrigation events in CROPWAT were set to occur at 100% depletion (i.e. when the soil moisture fell below the irrigation threshold) and the application was set to refill to 100% of field capacity. These parameters were selected to try to replicate the procedures used in the IRM to determine the timing of irrigation events.

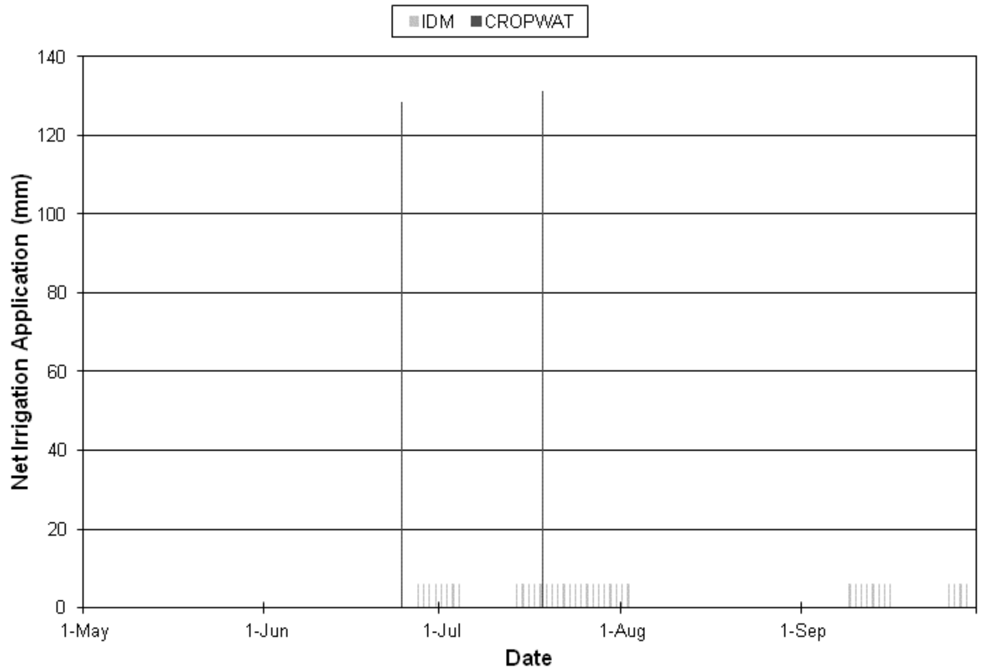


Figure 27 Optimum irrigation schedules calculated by the IDM and CROPWAT for a field of barley with fine soil for 2009 weather conditions irrigated with a sprinkler pivot high pressure irrigation system

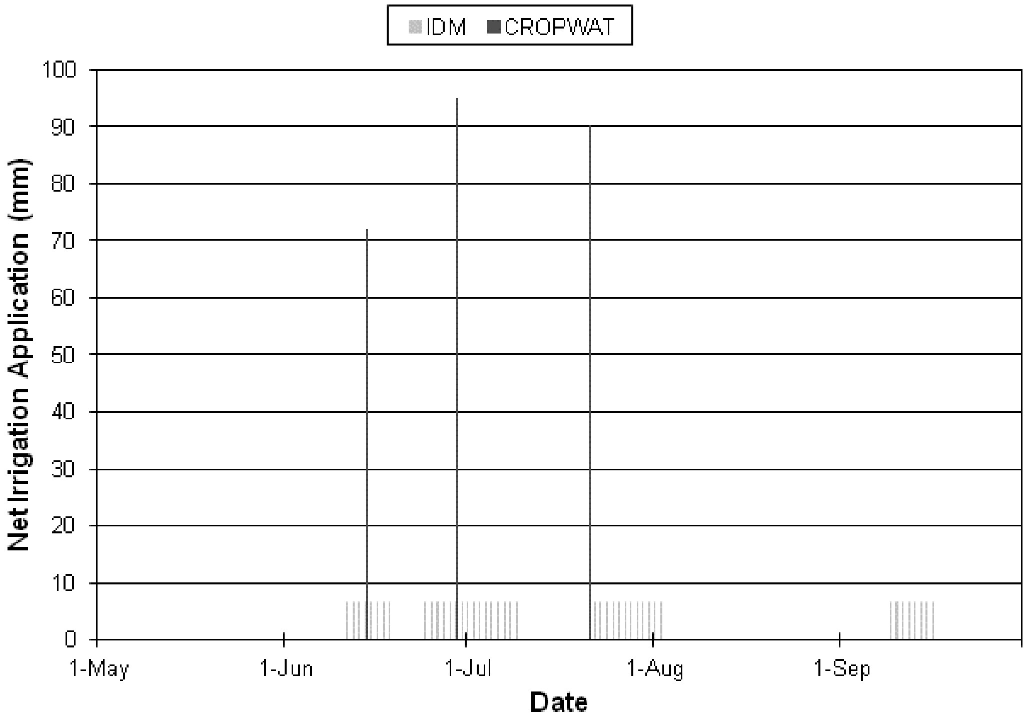


Figure 28 Optimum irrigation schedules calculated by the IDM and CROPWAT for a field of hard spring wheat with medium soil for 2009 weather conditions irrigated with a sprinkler pivot low pressure irrigation system

The optimal irrigation schedules for the IDM and CROPWAT in Figure 27 and Figure 28 show several similarities and differences that will be discussed in detail below. The causes of the differences in the timing of irrigation events are discussed first, followed by the differences in irrigation application amounts.

For barley in the two models, the first irrigation event occurred in the last week of June; while the second event occurred in mid July. Similarly, for hard spring wheat, the irrigation events occurred in the second week of June, the last week of June and first week of July, and finally, the last week of July. In general, the small differences between the onset dates of irrigation events between the two models are due to a combination of several factors:

- The randomized seeding date flag in the IDM might shift the seeding date from the seeding date specified for each crop that was used in CROPWAT. This would influence the first day that the crop would require water. For example, for barley the first day that the crop required water in the IDM was May 4th, while in CROPWAT it was April 30th. As a result, the first irrigation event in CROPWAT occurred earlier than in the IDM as seen in Figure 27.

- The randomized irrigation threshold flag in the IDM will modify the level at which the model will begin irrigating which could delay or expedite an irrigation event compared to CROPWAT which will always irrigate at 100% depletion. It is difficult to know exactly what the irrigation threshold was for a particular irrigation event in the IDM because the irrigation threshold is recalculated after each irrigation event and it is not included as part of the model's field output.

- The differences between the crop coefficient curves in the IDM and CROPWAT (see Figure 19) might result in slightly different crop water requirements between the two models.

- The different formulas used to calculate effective precipitation in the two models could cause differences in the soil moisture balance calculations.

However, the difference was negligible: for barley the runoff was roughly 8 mm in both models, while for wheat the difference between the two models was less than 3mm.

- The initial soil moisture in both models influences the soil moisture level at the time of planting and throughout the irrigation season. In the IDM, the initial soil moisture is set for the beginning of the simulation period at 50% as a percentage of the total available moisture. Normally, the IRM is run for one extra year at the beginning of the intended simulation period to ensure that the soil moisture has time to stabilize, so the soil moisture level at the time of planting is not necessarily 50% but usually close to field capacity. Note that even if the IRM were run for only one year, the soil moisture at the time of planting would not necessarily be 50% because of winter precipitation. Simulation runs in CROPWAT can only be run for one year beginning at the time of planting so that the initial soil moisture is actually the soil moisture at the beginning of the growing season and not at the beginning of the year. When the initial soil moisture fraction was set to 0.50 to coincide with the value used in the IRM, this value caused an irrigation event on the day of planting in CROPWAT that did not occur in the IRM. An initial soil moisture depletion of 0% was used instead to eliminate the irrigation event. Different initial soil moisture depletion values would shift the onset of the first irrigation event.

- Other differences between the procedures used to calculate the soil water balance between the two models (for example, simulation of root growth and percolation losses), could also result in small differences in the soil moisture level at any point during the simulation that could cause differences in the timing of the irrigation event.

In terms of application amounts, in the IDM a field is divided into bands, where a band is the portion of a field that is irrigated in one day based on the irrigation system coverage rate. The number of bands, and consequently the number of days required to complete an irrigation event in a field, depend of the type of irrigation system and the total area of the field. An irrigation event usually takes more than one day, as shown in Figure 27. Irrigation starts on the day when the average soil moisture in the field falls below the irrigation threshold and stops when all the bands have been irrigated. In CROPWAT, irrigation events are completed in one day as shown in Figure 27.

An important difference between the irrigation schedules calculated by the IRM and CROPWAT is the simulation of fall irrigation. Figure 27 shows two fall irrigation events for the field of barley; while Figure 28 shows one fall irrigation event for the field of hard spring wheat. CROPWAT stops irrigating after the harvest date.

Net irrigation application amounts for individual irrigation events were higher in CROPWAT compared to the IDM. For barley, the first two irrigation events were

61 and 152 mm according to the IDM, and 129 and 131 mm according to CROPWAT, yielding sums of 213 and 260 mm for the IDM and CROPWAT, respectively. For hard spring wheat, the first three irrigation events were 53, 106, and 80 mm according to the IDM, and 72, 95 and 90 mm according to CROPWAT, yielding sums of 239 and 257 mm. The percent differences between CROPWAT and the IDM's estimates were 22 % for barley and 7% for hard spring wheat.

An advantage of using the IRM to calculate irrigation schedules is that it calculates downtime losses and irrigation returns associated with gravity systems and CROPWAT does not.

In conclusion, the IDM and CROPWAT use different methods to calculate crop water requirements and irrigation applications, so they produce slightly different schedules for optimum irrigation even when the parameters used by both models are selected to be as similar as possible. The behaviour modelled in the IDM is more realistic than CROPWAT because it incorporates field realities such as variable seeding dates, observed daily crop coefficients, estimates of the actual time taken to irrigate a field depending on the irrigation technology in place, and the common practice of fall irrigation. Therefore, for optimum irrigation schedules, the IDM is more dependable than CROPWAT. Closer agreement between the two models would require further calibration of CROPWAT. However, when using CROPWAT to simulate scenarios that are not possible with the IDM, like in the two remaining scenarios explored here, the main thing to keep in mind is CROPWAT's tendency to calculate higher crop water requirements and irrigation applications compared to the IDM.

II. Fixed irrigation amount evenly distributed over a number of irrigation events with no irrigation during the initial stage and late season.

The second set of simulations was set up to simulate a water restriction scenario of 4 inches/acre (251 mm/ha) with CROPWAT. Recall that CROPWAT does not have an option for a fixed maximum irrigation application depth. Therefore, fixed irrigation intervals per stage combined with an appropriate user defined application depth were selected to simulate a total gross irrigation application of roughly 250 mm over the season. Intervals of 10 days were selected for the development stage and mid season; while intervals of 30 days were selected for the initial stage and late season. The choice of irrigation intervals was based on the following logic: (1) irrigation applications during the development stage and mid season were prioritized because these two growth stages are more sensitive to water than the initial stage and late season; (2) an interval of 30 days for the least water sensitive stages ensured no irrigation occurred during the initial stage and late season because the length of these stages is shorter than 30 days; and (3) an interval of 10 days (roughly one week) for the water sensitive stages ensured that irrigation events occurred often enough to supply enough water to the crop. The choice of irrigation intervals lead to user defined application depths of 22 mm each, so that the total application over the season equalled 254 mm. Note that the choice of 10 and 30 days was somewhat arbitrary. Longer irrigation intervals would result in fewer irrigation events and higher irrigation application depths and vice versa. Alternative simulations could use various irrigation intervals depending on the growth stages the user wishes to prioritize and reasonable spacing between irrigation events.

Table 16 shows the irrigation schedule modified from CROPWAT output for a representative field of hard spring wheat in medium soil in Block A under a total gross irrigation amount of 254 mm. The table shows for each irrigation event, the net irrigation application (mm), cumulative gross irrigation application (mm), the level of water stress in the plant (represented by the water stress coefficient k_s; the ratio of actual ET compared to potential ET, %; the root zone depletion relative to the total available water, %; and the irrigation deficit, mm), as well as any unused irrigation (loss, mm).

Table 17 shows for each growth stage and the entire season, the reductions in ET_c (%), yield response factor and yield reduction (%). The yield response factors for individual growth stages were taken from the standardized crop data provided in CROPWAT files and are intended for comparison of the relative water sensitivity between stages only. The yield response factor for the entire season was taken from Bennett and Harms (2011). Note that the yield reduction for the entire season was calculated using the yield response factor for the entire season and not a weighted average based on the individual growth stages.

Table 17 shows that for this irrigation schedule, the reduction in evapotranspiration was 15.8% and the yield reduction was 18.1% for the entire season. The yield reduction result was higher than the average yield reduction for hard spring wheat calculated using Bennett and Harm's relationships and IDM output of 4%. Recall, however that CROPWAT calculates higher crop water requirements than the IDM so under a fixed irrigation application, CROPWAT calculates a higher yield reduction.

Table 16 Irrigation schedule for hard spring wheat under water restriction scenario calculated by CROPWAT

Date	Day	Stage	Net Irr. mm	Cum. Gr. Irr. mm	Ks Fract.	ET_a %	Depl %	Irr. Deficit mm	Loss mm
9 May	10	Dev	22.0	28.2	1.00	100	1	0.0	21.6
19 May	20	Dev	22.0	56.4	1.00	100	11	0.0	13.5
29 May	30	Dev	22.0	84.6	1.00	100	27	6.2	0.0
9 Jun	40	Dev	22.0	112.8	1.00	100	24	8.3	0.0
18 Jun	50	Dev	22.0	141.0	1.00	100	36	32.9	0.0
28 Jun	60	Dev	22.0	169.2	1.00	100	54	75.7	0.0
8 Jul	70	Mid	22.0	197.4	0.90	96	59	83.7	0.0
18 Jul	80	Mid	22.0	225.6	0.56	80	74	112.1	0.0
28 Jul	90	Mid	22.0	253.8	0.42	54	80	122.1	0.0
22 Aug	End	End			0.92	0	54		

Table 17 Yield reductions for hard spring wheat under water restriction scenario calculated by CROPWAT

Stage	Initial	Development	Mid Season	Late Season	Total
Reductions in ET_c (%)	0.0	0.0	24.2	35.6	15.8
Yield response factor	0.40	0.60	0.80	0.40	1.15
Yield reduction (%)	0.0	0.0	19.3	14.2	18.1

However, the main difference between the yield reduction calculations in CROPWAT and the estimates of yield reductions using output from the IDM is that in CROPWAT, the crop evapotranspiration ET_a is adjusted under soil water stress conditions on a daily basis. CROPWAT captures the response of crops to water stress by reducing actual evapotranspiration when the crop is subjected to water deficits. The calculation follows the guidelines for computing crop water requirements by Allen *et al.* (1998) using Equation 9:

$$ET_a = k_s k_c ET_o \tag{9}$$

The water stress coefficient, k_s, ranges from 0 to 1and describes the effect of water stress on crop transpiration according to Equation 10:

$$k_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW} \tag{10}$$

where D_r is the root zone depletion (mm), TAW is the total available soil water in the root zone (mm), RAW is the readily available soil water in the root zone (mm) and p is the fraction of TAW that a crop can extract from the root zone without suffering water stress. Further, TAW is defined by Equation 11:

$$TAW = 1000\,(\theta_{FC} - \theta_{WP})Z_r \tag{11}$$

where θ_{FC} is the water content at field capacity (m^3/m^3), θ_{WP} is the water content at wilting point (m^3/m^3) and Z_r is the rooting depth.

Table 16 shows that the water restriction scenario with 10 day interval irrigation events did not lead to significant water stress during the development stage – the value of k_s remained at 1.00 and as a result, the actual evapotranspiration was 100% of the potential evapotranspiration. In fact, the first two irrigation events resulted in unused irrigation (losses) because the depletion levels were low and the irrigation applications were practically unnecessary (Figure 29). However, the irrigation deficit accumulated during the mid season leading to depletion levels higher than the readily available soil moisture in the root zone (Figure 29). The frequency and magnitude of the irrigation events were not adequate for optimal crop growth. This situation led to reductions in ET_a (Table 16) which in turn resulted in yield reductions (Table 17). Depletion levels were also high during the late season from day 90 to harvest (since no irrigation events were allowed) which led to additional yield reductions (Table 17).

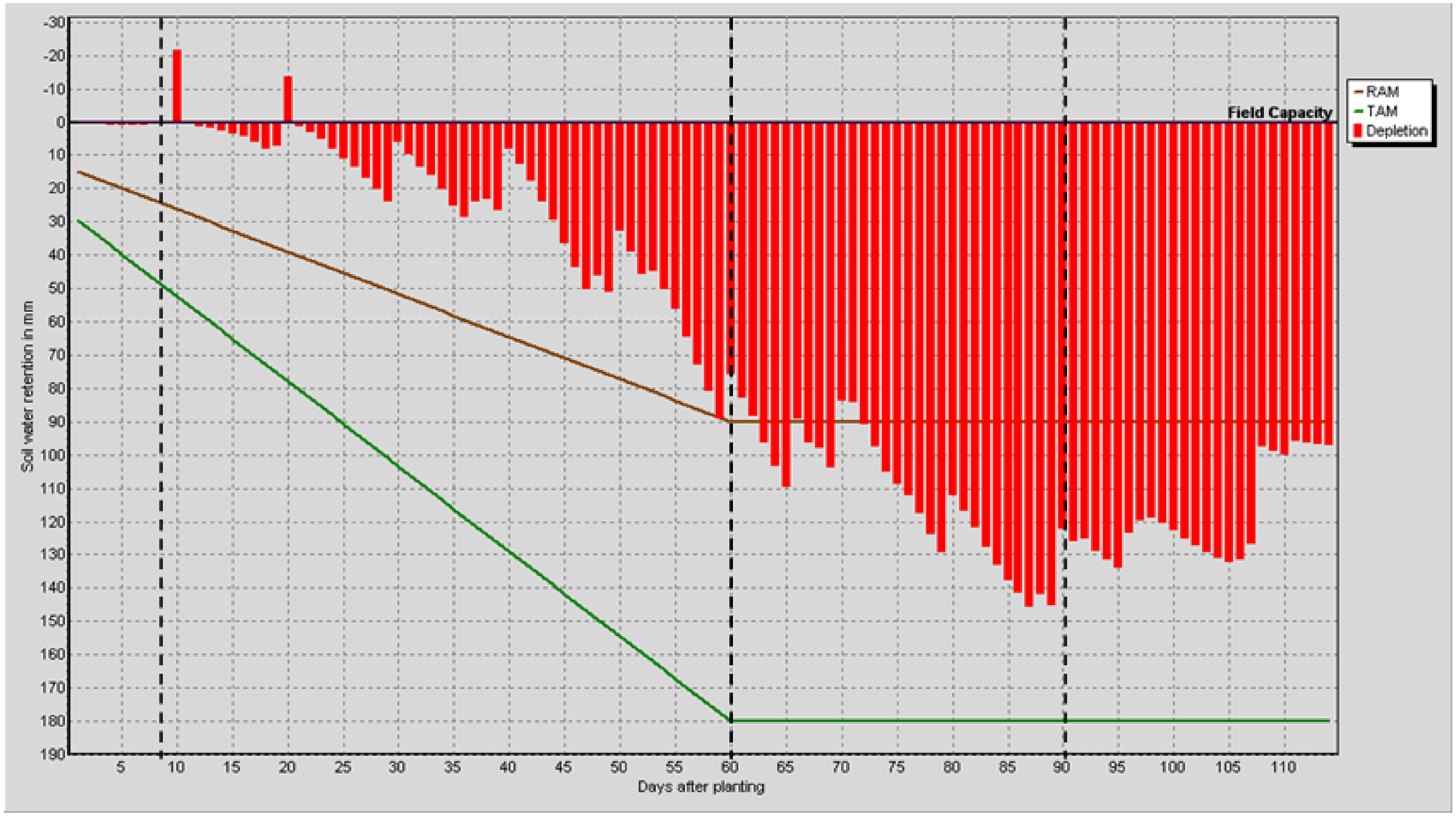


Figure 29 Irrigation scheduling graph generated by CROPWAT showing root zone depletion (mm), total available soil moisture in the root zone (TAM i.e. TAW) (mm), and the readily available soil moisture in the root zone (RAM i.e. RAW) (mm) for wheat under water restriction scenario

Knowledge of the distribution of crop water requirements and the sensitivity of different crop growth stages to water stress could be used to optimize the irrigation schedule for maximum yield given a fixed water application amount. Crop water requirements are a function of the crop coefficient curve which increases during the development stage, is highest during the mid season, and finally decreases during the late season. In an optimization exercise, the stages with highest crop water requirements should be prioritized. Crop coefficient curves are available from the IDM database. In contrast, the yield response factors that characterize the water sensitivity of different growth stages are not actually known for Alberta – the pre-defined factors in CROPWAT were used here to give an idea of the relative magnitude between the different growth stages. The optimization exercise would involve running CROPWAT manually for a series of irrigation intervals and applications until satisfactory results were found. Note that CROPWAT cannot automatically find optimal schedules based on a fixed total irrigation depth.

Table 18, Table 19 and Figure 30 show CROPWAT results for an irrigation schedule based on a fixed gross irrigation amount of 251 mm (4 inches/acre) with slightly lower yield reductions (16.9%) compared to the one presented above. The schedule had irrigation intervals of 30, 25, 8 and 15 days for the initial stage, development stage, mid season and late season, respectively, and fixed application depths of 28 mm. Increasing the irrigation interval during the development stage reduced the number of irrigation events from six to two, reducing the irrigation losses and thus the water that was not beneficially used. Decreasing the irrigation interval during the mid season decreased the reductions in ET_c during this stage which was beneficial since this stage is the most sensitive to water stress. Further, introducing irrigation events every 15 days during the late season also decreased the reductions in ET_c during the late season with positive consequences on yield.

Table 18 Irrigation schedule for hard spring wheat under water restriction scenario calculated by CROPWAT

Date	Day	Stage	Net Irr. mm	Cum. Gr. Irr. mm	Ks Fract.	ET_a %	Depl %	Irr Deficit mm	Loss mm
24 May	25	Dev	28.0	35.9	1.00	100	22	0.0	8.1
18 Jun	50	Dev	28.0	71.8	0.94	99	56	59.1	0.0
29 Jun	61	Mid	28.0	107.7	0.69	91	69	95.5	0.0
7 Jul	69	Mid	28.0	143.6	0.82	87	62	83.7	0.0
15 Jul	77	Mid	28.0	179.5	0.73	90	66	91.5	0.0
23 Jul	85	Mid	28.0	215.4	0.50	72	77	111.1	0.0
7 Aug	100	End	28.0	251.3	0.63	63	70	97.8	0.0
22 Aug	End	End			1.00	0	43		

Table 19 Yield reductions for hard spring wheat under water restriction scenario calculated by CROPWAT

Stage	Initial	Development	Mid Season	Late Season	Total
Reductions in ET_c (%)	0.0	2.8	20.6	31.2	14.7
Yield response factor	0.40	0.60	0.80	0.40	1.15
Yield reduction (%)	0.0	1.7	16.4	12.5	16.9

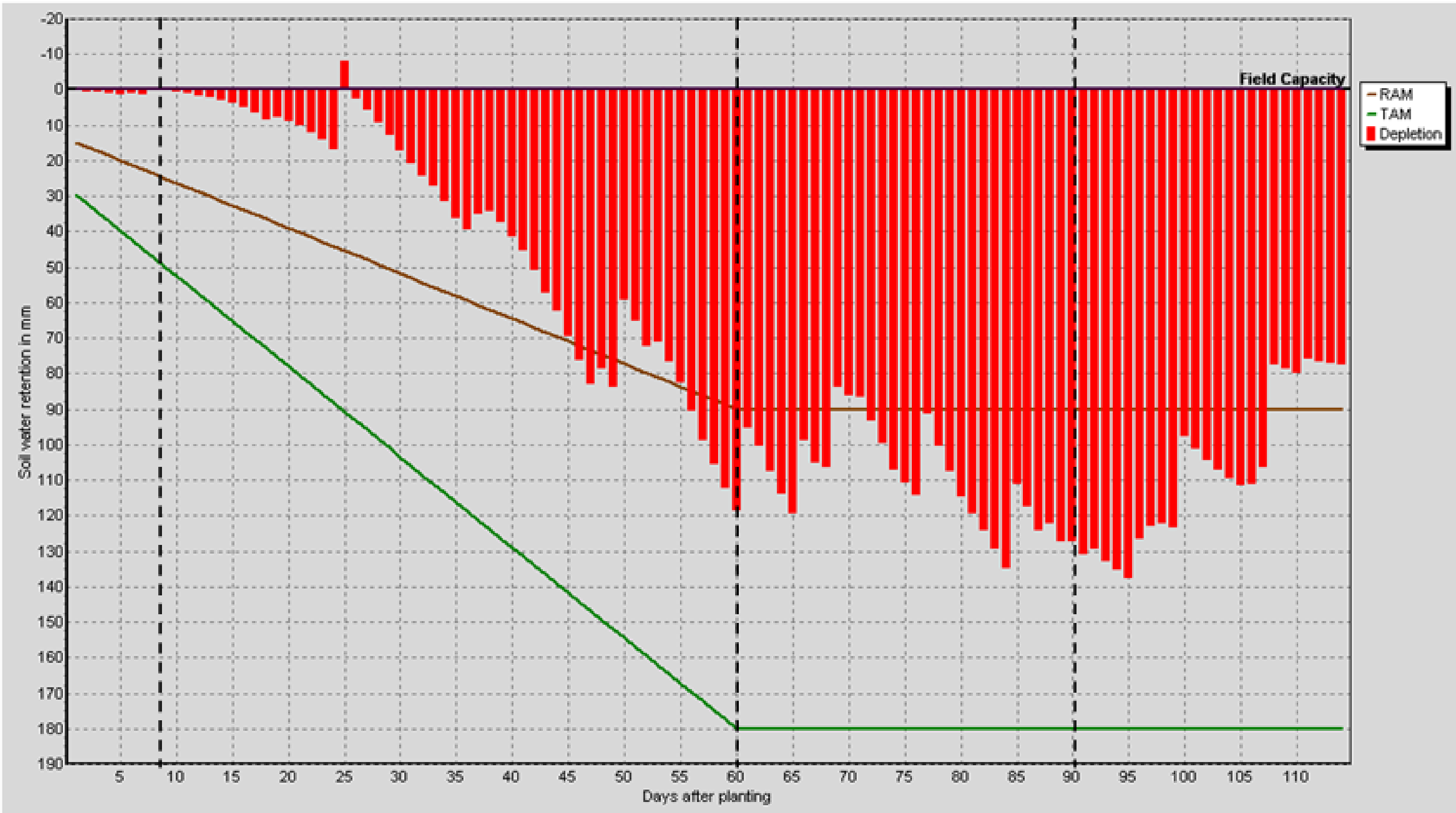


Figure 30 Irrigation scheduling graph generated by CROPWAT showing root zone depletion (mm), total available soil moisture in the root zone (TAM i.e. TAW) (mm), and the readily available soil moisture in the root zone (RAM i.e. RAW) (mm) for wheat under water restriction scenario

III. Deficit irrigation by imposing water stress throughout the growing season

The third set of simulations was set up to simulate deficit irrigation by allowing the depletion to fall below the critical depletion thus inducing water stress on the plant.

Table 20 compares the reductions in evapotranspiration and yield for three deficit irrigation treatments for a representative field of hard spring wheat in medium soil in Block A. Irrigation was applied when the available soil moisture in the root zone was depleted to 20 - 50% of the total available soil moisture (50 – 80% depletion). Note that 50% depletion of the total available soil moisture is equivalent to optimum irrigation since the critical depletion fraction for wheat is 50%. Table 20 shows that the reductions in ET_c occurred primarily during the development stage and mid season for the 30 and 40% depletion levels, and during the late season for the 20% depletion level. Further, Table 20 shows the total gross irrigation associated with each deficit irrigation treatment. According to these results, the total gross irrigation amount could be reduced by about 35 mm with a yield reduction of 1.2%, and by 115 mm with a yield reduction of 6.8 %.

Table 20 Reductions in ET_c for each growth stage, yield reductions and total gross irrigation amounts for four levels of depletion for a representative field of hard spring wheat as calculated by CROPWAT

Depletion level (% of TAW)	Initial Stage	Develop. Stage	Mid Season	Late Season	Total Season	Yield reduction (%)	Total Gross Irr. (mm)
20%	0.0	16.7	16.1	46.0	20.6	23.7	187.2
30%	0.0	9.7	4.2	0.3	5.9	6.8	316.9
40%	0.0	0.9	1.6	0.0	1.1	1.2	395.3
50%	0.0	0.0	0.0	0.0	0.0	0.0	431.3

The three scenarios investigated with CROPWAT demonstrated the potential application of the model to study irrigated crop yields under reduced water supply in the WID and elsewhere in southern Alberta. The following conclusions can be drawn:

1. CROPWAT requires weather, crop, soil, and irrigation technology data that are available from the IDM database (except for soil infiltration rates and yield response factors). However, some of the data, such as the crop coefficient curves, needs to be adapted to fit CROPWAT's requirements. The initial soil moisture also requires some calibration to ensure the soil moisture at planting in CROPWAT matches the soil moisture in the IDM. As a result of these situations, CROPWAT calculated higher crop water requirements compared to the IDM for optimum irrigation.

2. The IDM and CROPWAT use different procedures to determine irrigation applications that cause differences between the irrigation schedules for optimum irrigation produced by the two models. CROPWAT simulates

irrigation to less detail than the IDM; for example, the IDM includes fall irrigation and variability in seeding dates and irrigation threshold, while CROPWAT does not.

3. CROPWAT incorporates a wide range of irrigation scheduling options that can be used to simulate a fixed seasonal irrigation application depth. The model could be applied to find optimal schedules for a limited amount of water with minimal yield reductions.

4. Yield reductions in CROPWAT are modelled more accurately than in the calculations with IDM output and Bennett and Harm's (2011) equations because daily actual evapotranspiration is reduced when the crop is subjected to water deficits; whereas the IDM calculations consider only total seasonal evapotranspiration when calculating yield.

5. Finally, CROPWAT is well suited to simulate deficit irrigation by imposing different levels of water stress on a crop. Unfortunately, the level of depletion cannot be specified for individual growth stages. Still, CROPWAT could be used to compare the effects of supplying less than optimum irrigation applications and the relative water sensitivity of different growth stages.

In summary, the methodology presented here using output from the IDM and available empirical relationships from Bennett and Harms (2011) is suitable as a first step towards assessing the effects of water application restrictions at a wide district level. Even though the methodology has limitations, the crop water and yield relationships are simple and easy to apply given the data available from the IDM. The yield reduction estimates are reasonable but irrigation managers should focus on qualitative, rather than quantitative analysis. The estimates should be used to analyze the role of crop type, irrigation system efficiency and weather conditions.

CROPWAT is better suited to study the effects of reduced water supply on crops and could be used to study how a water application restriction would be implemented at the field level. Using CROPWAT versus the IDM has several tradeoffs. In the one hand, the IDM provides a lot of detail about the fields in the district, but little accuracy in the calculation of yields. CROPWAT, on the other hand, provides solid estimates of yield reductions as long as yield response factors are known, but representative fields with generalized or average characteristics need to be used.

Finally, for detailed agronomic research on deficit irrigation, more complex models such as Aquacrop would be more appropriate. These would need to be calibrated and validated with experimental data for conditions experienced in southern Alberta.

5 Conclusions and Recommendations

5.1 Conclusions

Irrigation is essential to meet current and future food demands. In Alberta, irrigation districts are important water use stakeholders, who are experiencing increasing pressure to improve their water use efficiency and reduce their water demand. The WID, in particular, faces significant challenges in improving its water use efficiency – because of exposure to increasing urban and industrial pressures, a conveyance system that has undergone little rehabilitation, a lack of reservoir storage, and long irrigation water travel times. Improving water use efficiency in the WID and other districts will require a combination of approaches that address both water supply and demand. This research explored full rehabilitation and implementation of most efficient technologies, and water application restrictions as two means of achieving water savings in the WID.

Simulation of rehabilitation of WID infrastructure and implementation of most efficient irrigation technologies scenarios with the Irrigation Demand Model (IDM) showed that water use could be reduced at the farm-, conveyance system- and district levels as a result of decreased on-farm and system losses. The total district demand could decrease by 2% from the baseline with the conversion of small laterals into pipelines; by 5% with additional lining of earth canals; and by 10% with added implementation of most efficient technologies – the latter represented an “ideal case” district modernization scenario. Installation of pipeline and clay lining of earth canals would reduce canal seepage and canal evaporation losses, while a complete shift from gravity systems, hand move, wheel move, and high pressure sprinkler to more efficient low pressure sprinklers would lower evaporation losses and eliminate return flows from gravity systems. Note, however, that the total district demand estimates in the IDM are known to be accurate to within 10%, so the fine differences presented here may not be significant. The major limitation in the study was estimating the return flow fraction for a rehabilitated WID canal system – with closed pipeline laterals instead of open canals – because the IDM does not simulate water flows, only water demands. Moreover, water savings from changes to the conveyance and irrigation systems are limited in practice by physical, economical and operational constraints. Water use efficiency calculated using four different indicators increased with irrigation modernization; however, the degree of improvement from the baseline depended heavily on the definition used and ranged from 2 to 11% for the "ideal case" scenario. In conclusion, even with extensive district modernization, the WID is unlikely to meet the goal of 30% improvement in water use efficiency stated in the *Water for Life* strategy with changes to the physical and technical components of the irrigation system alone.

Results of the simulation of water restriction scenarios of 8, 6 and 4 inches/acre (equivalent to 502, 377 and 251 mm/ha) for the WID showed that imposing limits on maximum water applications would affect crops differently depending on yearly weather conditions, location in the district and the irrigation system efficiency. Alfalfa, the most widely-grown crop in the WID, would be the most affected at the three restriction levels because of its high irrigation water requirements. Other common crops like barley, barley silage, canola, wheat and tame pasture would be affected to a much lesser degree. Imposed limits of 8 and 6 inches/acre (502 and 377 mm/ha) would satisfy optimum gross irrigation application demands for most crops except alfalfa, while a 4 inches/acre (251 mm/ha) limit would result in irrigation deficits for most crops. Thus, yield reductions could be expected for alfalfa even at low or moderate levels of water restriction, while significant yield reductions for other crops could be expected only under strict water restrictions or during dry years. Setting the water application restriction level at 8 inches/acre (502 mm/ha) as the starting point would be justified since it would have little effect on crop yields other than alfalfa. A 6 inches/acre (377 mm/ha) would still be reasonable, since it would ensure adequate supply for most crops, but it would require considerable support from and special considerations for alfalfa growers.

Water productivity for the district could be increased if the water saved were used to irrigate more land; however, this research did not attempt to estimate the potential increases in productivity from using the water saved to irrigate a larger area. Ideally, the simulation results would have included estimates of the total district demand under water restriction scenarios to quantify the water savings. Unfortunately, this was not possible because of the limitations of the IDM. In any case, given the large volumes of water needed to “move” water through the WID conveyance system – the base flow – the total water demand is likely to remain high even though the water consumed at the farm level would be less.

In terms of simulation tools, the two scenarios explored for the WID in this research demonstrated several strengths and weaknesses of the IDM for modelling irrigation management scenarios in Alberta. The IDM is a suitable model for calculating irrigation water demands in the irrigation districts and a reliable tool for planning and long-term, strategic decision making. The model contributes a comprehensive database of irrigated crop characteristics, irrigation technology, conveyance infrastructure, and weather conditions. The IDM adequately represents the complex field realities, weather conditions and irrigation infrastructure in the districts. However, the potential water shortages in Alberta stress the need to focus on irrigation water management scenarios under potentially reduced water supplies. These types of scenarios are difficult or impossible to simulate with the IDM because they involve managerial aspects that the IDM does not include.

The methodology presented here to quantify the effects of imposing district-wide restrictions on water applications provides first-order estimates of yield reductions and identifies the role played by crop type, irrigation system efficiency and weather conditions. However, current modelling tools in Alberta, other than perhaps the FFIRM, are not capable of simulating the effects of reduced water supply on crop yields to the extent that is required for better yield-reduction estimates. Simulations with CROPWAT demonstrated the value of an exploration of alternative irrigation scheduling options, including the impact of water stress during particular growth stages and the consequences of deficit irrigation. CROPWAT can be run with data from the IDM's database after appropriate calibration. Yet, using CROPWAT for simulations where the relative difference between growth stages is important (for example, deficit irrigation treatments that prioritize water supply during particular growth stages) would require yield response factors (k_y) for individual growth stages that are not currently known for southern Alberta.

If irrigation districts are forced to compete with other water users, and water available for irrigation is reduced due to changes in management or available water supply, deficit irrigation may become a viable way to reduce agricultural water consumption while maintaining acceptable yields. Deficit irrigation has not been studied widely in Alberta as a potential way to improve water productivity, although it has been investigated elsewhere as a strategy to maximize water productivity in dry regions, where water supplies are limited. More experimental data on yield responses to water stress for conditions in southern Alberta's irrigation districts are needed to validate existing crop yield to water relationships and use as input for modelling tools – such data are currently lacking (personal communication with Shelley Woods, ARD, December 2011). This data includes yield response factors, k_y, for commonly grown crops including for specific crop growth stages. Preliminary simulations of deficit irrigation using CROPWAT for a representative field of hard spring showed possible yield reductions of 1.2% and 6.8% which saved 35 and 115 mm, respectively of the seasonal gross irrigation applications.

5.2 Recommendations

Future research on irrigation water management in Alberta could focus on one or more of the following areas:

- Development of a model of district operations. This model could incorporate, at least in a simplified way, the operational rules of reservoirs and time delays associated with a district's infrastructure to model the conveyance of water. Ideally, this model would incorporate existing conveyance infrastructure data from the IDM database through a GIS interface. A model of this type would be of interest not only to ARD for policy-making, but also to irrigation district managers as they could use it to investigate current operational constraints and to explore viable options for district modernization. Important aspects to model include: the tension between supply and demand, the role of base flow and adequate calculations of the return flow. Additionally, the model could simulate different irrigation scheduling options and the effect of water stress on crop yields. The models described in section 2.3.3 incorporate many of these features and could be used as a reference. This type of research could be conducted by academics (likely a PhD student) with input from

Alberta Agriculture and Rural Development and irrigation district managers.

- Further economic analysis of water restriction scenarios. This work would require updated information on crop pricing and other inputs. The newly updated FFIRM model could be used as a modelling tool for this purpose, but simulations would have to be conducted by Alberta Agriculture and Rural Development. Yield reductions under water restrictions could also be calculated for other irrigation districts using a similar approach to that presented here to assess the impact of imposing water application limits on crop yields for different weather parameters and crop mixes.

- Lastly, additional calibrations and simulations with CROPWAT to explore deficit irrigation practices could be conducted. Such scenarios could inform the implementation of water restriction applications and other irrigation management options at the field level. Alternatively, a model like AquaCrop could be tested with appropriate experimental data; however, this option would address the issue of deficit irrigation more from an agronomic point of view, rather than from a water management perspective.

6 References

Abrahamsen, P., and S. Hansen. 2000. Daisy: An open soil-crop-atmosphere system model. *Environmental Modelling & Software* 15 (3): 313-30.

Alberta Agriculture and Rural Development. 2000. *Irrigation in Alberta*. Lethbridge, Alberta: Technology & Innovation Branch of Alberta Agriculture and Food (AF).

Alberta Agriculture and Rural Development. 2004. *Alberta's Agriculture Growth Strategy: $20/$10 by 2010 Driving Sustainable Growth.* Alberta: Government of Alberta.

Alberta Agriculture and Rural Development. 2010. *Alberta Irrigation Information: Facts and figures for the year 2009*. Lethbridge, Alberta: Alberta Agriculture and Rural Development.

Alberta Agriculture and Rural Development. 2011. *Alberta Irrigation Information: Facts and figures for the year 2010*. Lethbridge, Alberta: Alberta Agriculture and Rural Development.

Alberta Agriculture, Food and Rural Development Irrigation Branch. 2011. *Alberta Irrigation Management Model (AIMM).* www.imcin.net/aimm_tech_doc.pdf (Accessed September 24, 2011)

Alberta Economic Development Authority. 2008. *Sustainable Water Management and Economic Development in Alberta*.

Alberta Environment. 2002a. *Water for Life - Facts and information on water in Alberta*. Edmonton, Alberta: Alberta Environment.

Alberta Environment. 2002b. *Water Resources Management Model - computer program description*. Calgary, Alberta: Alberta Environment.

Alberta Environment. 2003. *Water for life: Alberta's strategy for sustainability*. Edmonton, Alberta: Alberta Environment.

Alberta Environment. 2006. *Approved water management plan for the South Saskatchewan River Basin (Alberta)*. Alberta: Alberta Environment.

Ali, M. K., D. G. Le Roy, and K. K. Klein. 2010. *Water allocation models for Alberta: What's available and what are the needs?* SAREC report 2010-3. Lethbridge, Alberta: Southern Alberta Resource Economics Centre.

Ali, M. H. 2011. *Practices of irrigation & on-farm water management. volume 2 [electronic resource]*. New York: Springer, 546 pp.

Ali, M. H., M. R. Hoque, A. A. Hassan, and A. Khair. 2007. Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. *Agricultural Water Management* 92 (3): 151-61.

Ali, M. H., and M. S. U. Talukder. 2008. Increasing water productivity in crop production—A synthesis. *Agricultural Water Management* 95 (11): 1201-13.

Ali, M. H., L. T. Shui, and W. R. Walker. 2003. Optimal water management for reservoir based irrigation projects using geographic information system. *Journal of Irrigation and Drainage Engineering* 129 (1): 1-10.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper* number 56. Rome: FAO.

AMEC Earth & Environmental. 2007. *Current and future water use in Alberta*. Edmonton, Alberta: Alberta Environment.

Bazzani, G. M. 2005. An integrated decision support system for irrigation and water policy design: DSIRR. *Environmental Modelling & Software* 20 (2): 153-63.

Bennett, D. R., and T. Harms. 2011. Crop yield and water requirement relationships for major irrigated crops in southern Alberta. *Canadian Water Resources Journal* 36 (2): 159-70.

Bjornlund, H., L. Nicol, and K. K. Klein. 2007. Challenges in implementing economic instruments to manage irrigation water on farms in southern Alberta. *Agricultural Water Management* 92 (3): 131-41.

Bjornlund, H., L. Nicol, and K. K. Klein. 2009. The adoption of improved irrigation technology and management practices-A study of two irrigation districts in Alberta, Canada. *Agricultural Water Management* 96 (1): 121-31.

Bow River Basin Council. 2005. *Nurture, renew, protect: A report on the state of the Bow River Basin*. Calgary, Alberta: Bow River Water Council.

Burt, C. M., et al. 1997. Irrigation performance measures: Efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* 123 (6): 423-42.

Chavez-Morales, J., M. A. Marino, and E. A. Holzapfel. 1992. Planning simulation model of irrigation district. *Journal of Irrigation and Drainage Engineering* 118 (1): 74-87.

De Nys, E., P. Le Gal, D. Raes, and E. Ana. 2008. WaDI (water delivery for irrigation): A simulation tool to address strategic interaction of water demand and supply in irrigation schemes. *Agricultural Water Management* 95 (3): 224-32.

Dechmi, F., E. Playán, J. M. Faci, and M. Tejero. 2003a. Analysis of an irrigation district in northeastern spain: I. characterisation and water use assessment. *Agricultural Water Management* 61 (2): 75-92.

Dechmi, F., E. Playán, J. M. Faci, M. Tejero, and A. Bercero. 2003b. Analysis of an irrigation district in northeastern spain: II. irrigation evaluation, simulation and scheduling. *Agricultural Water Management* 61 (2): 93-109.

Döll, P. 2002. Impact of climate change and variability on irrigation requirements: A global perspective. *Climatic Change* 54 (3): 269-93.

Doorenbos, J., and A. H. Kassam. 1979. Yield response to water. *FAO Irrigation and Drainage Paper* number 33. Rome: FAO.

Doorenbos, J., and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper* number 24. Rome: FAO.

FAO. 2003. *World agriculture towards 2015/2030: An FAO perspective*. London: Earthscan Publications Ltd.

FAO. 2012a. *AQUASTAT - FAO's information system on water and agriculture, water use*. http://www.fao.org/nr/water/aquastat/water_use/index.stm. (Accessed August 30, 2012).

FAO. 2012b. *Example of the use of CROPWAT 8.0.* http://www.fao.org/nr/water/docs/CROPWAT8.0Example.pdf (Accessed May 3, 2012).

Federer, C., C. Vorosmarty, and B. Fekete. 1996. Intercomparison of methods for calculating potential evaporation in regional and global water balance models. *Water Resources Research* 32 (7): 2315-21.

Fereres, E., and M. A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany* 58 (2): 147-59.

FAO, ed. 2002. *Deficit irrigation practices: Water report 22*. Deficit irrigation practices: Water reports 22. Rome: FAO.

Geerts, S., D. Raes, and M. Garcia. 2010. Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management* 98 (1): 213-6.

Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management* 96 (9): 1275-84.

George, B. A., S. A. Shende, and N. S. Raghuwanshi. 2000. Development and testing of an irrigation scheduling model. *Agricultural Water Management* 46 (2): 121-36.

Georgiou, P. E., and D. M. Papamichail. 2008. Optimization model of an irrigation reservoir for water allocation and crop planning under various weather conditions. *Irrigation Science* 26 (6): 487-504.

Gleick, P. H. 2003. Global freshwater resources: Soft-path solutions for the21st century. *Science* 302 (5650): 1524.

Government of Alberta. 2009. *Water for life: Action plan*. Edmonton, Albertaa.: Government of Alberta.

Hanson, B., D. Putnam, and R. Snyder. 2007. Deficit irrigation of alfalfa as a strategy for providing water for water-short areas. *Agricultural Water Management* 93 (1–2): 73-80.

Hexem, R. W., and E. O. Heady. 1978. *Water production functions for irrigated agriculture*. Ames, Iowa: Iowa State University Press.

Hoekstra, A., and P. Hung. 2005. Globalisation of water resources: International virtual water flows in relation to crop trade. *Global Environmental Change-Human and Policy Dimensions* 15 (1): 45-56.

Howell, T. A. 1990. Relationships between crop production and transpiration, evapotranspiration, and irrigation. In *Irrigation of agricultural crops - agronomy monograph no. 30.*, eds. B. A. Stewart, D. R. Nielsen. 1990th ed., 391-434. Madison, Wisconsin, USA: American Society of Agronomy; Crop Science Society of America; Soil Science Society of America;.

Howell, T. A., R. H. Cuenca, and K. H. Solomon. 1990. Chapter 5 Crop yield response. In *Management of farm irrigation systems* , eds. G. J. Hoffman, T. A. Howell and K. H. Solomon, 93-122. St. Joseph, MI: American Society of Agricultural Engineers.

Howell, T. A. 2001. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal* 93 (2): 281-9.

Hsiao, T. C., L. Heng, P. Steduto, B. Rojas-Lara, D. Raes, and E. Fereres. 2009. AquaCrop-the FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agronomy Journal* 101 (3): 448-59.

Irrigation Water Management Study Committee. 2002a. *South Saskatchewan River Basin Irrigation in the 21st century*. Vol. Volume 1: Summary Report. Lethbridge, Alberta: Alberta Irrigation Projects Association.

Irrigation Water Management Study Committee. 2002b. *South Saskatchewan River Basin Irrigation in the 21st century*. Vol. Volume 4: Modelling Irrigation. Lethbridge, Alberta: Alberta Irrigation Projects Association.

Irrigation Water Management Study Committee. 2002c. *South Saskatchewan River Basin Irrigation in the 21st century*. Vol. Volume 5: Economic Opportunities and Impacts. Lethbridge, Alberta: Alberta Irrigation Projects Association.

Jalota, S. K., A. Sood, J. D. Vitale, and R. Srinivasan. 2007. Simulated crop yields response to irrigation water and economic analysis: Increasing irrigated water use efficiency in the Indian Punjab. *Agronomy Journal* 99 (4): 1073-84.

Jensen, M. E. 1968. Water consumption by agricultural plants. In *Water deficits and plant growth*, ed. T. T. Kozlowski. Vol. 2, 1-22. New York: Academic Press.

Jensen, M. E., R. D. Burman, and R. G. Allen, eds. 1990. *Evapotranspiration and irrigation water requirements (Manual of practice no. 70)*. Manuals and Reports on Engineering Practice. New York: American Society of Civil Engineering.

Jensen, M. 2007. Beyond irrigation efficiency. *Irrigation Science* 25 (3): 233-45.

Jones, J. W., G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. Gijsman, and J. T. Ritchie. 2003. The DSSAT cropping system model. *European Journal of Agronomy* 18 (3-4): 235-65.

Kang, S., L. Zhang, Y. Liang, X. Hu, H. Cai, and B. Gu. 2002. Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. *Agricultural Water Management* 55 (3): 203-16.

Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, et al. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18 (3–4): 267-88.

Khan, S. and E. G. R. Davies, "Western Irrigation District Water Management and Conveyance: An Initial Report on Part I of "Water: Making do with what we have..."" 2011).

Khepar, S. D., H. S. Gulati, A. K. Yadav, and T. P. S. Brar. 2000. A model for equitable distribution of canal water. *Irrigation Science* 19: 191-197

Kirda, C. 2002. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. In *Deficit irrigation practices: Water report 22.*, 3-10. Rome: Food and Agriculture Organization of the United Nations.

Kuo, S., G. P. Merkley, and C. Liu. 2000. Decision support for irrigation project planning using a genetic algorithm. *Agricultural Water Management* 45 (3): 243-66.

Labbé, F., P. Ruelle, P. Garin, and P. Leroy. 2000. Modelling irrigation scheduling to analyse water management at farm level, during water shortages. *European Journal of Agronomy* 12 (1): 55-67.

Lecina, S., D. Isidoro, E. Playán, and R. Aragüés. 2010. Irrigation modernization and water conservation in Spain: The case of Riegos del Alto Aragón. *Agricultural Water Management* 97 (10): 1663-75.

Lecina, S., and E. Playán. 2006a. Model for the simulation of water flows in irrigation districts. I: Description. *Journal of Irrigation & Drainage Engineering* 132 (4): 310-21.

Lecina, S., and E. Playán. 2006b. Model for the simulation of water flows in irrigation districts. II: Application. *Journal of Irrigation & Drainage Engineering* 132 (4): 322-31.

Lecina, S., E. Playán, D. Isidoro, F. Dechmi, J. Causapé, and J. M. Faci. 2005. Irrigation evaluation and simulation at the irrigation district V of Bardenas (Spain). *Agricultural Water Management* 73 (3): 223-45.

Leenhardt, D., J. Trouvat, G. Gonzalès, V. Pérarnaud, S. Prats, and J. Bergez. 2004. Estimating irrigation demand for water management on a regional scale: I. ADEAUMIS, a simulation platform based on bio-decisional modelling and spatial information. *Agricultural Water Management* 68 (3): 207-32.

Mailhol, J. C., A. A. Olufayo, and P. Ruelle. 1997. Sorghum and sunflower evapotranspiration and yield from simulated leaf area index. *Agricultural Water Management* 35 (1–2): 167-82.

Mateos, L., I. López-Cortijo, and J. A. Sagardoy. 2002. SIMIS: The FAO decision support system for irrigation scheme management. *Agricultural Water Management* 56 (3): 193-206.

Molden, D., T. Oweis, P. Steduto, P. Bindraban, M. A. Hanjra, and J. Kijne. 2010. Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management* 97 (4): 528-35.

Nicol, L. A., H. Bjornlund, and K. K. Klein. 2008. Improved technologies and management practices in irrigation-implications for water savings in southern Alberta. *Canadian Water Resources Journal* 33 (3): 283-93.

Palmer, B. C., K. K. Krogman, K. D. Russell, and R. Woelke. 1982. *Irrigation water requirement criteria study - South Saskatchewan River Basin planning program, agronomy component*. Lethbridge, Alberta: UMA Engineering Ltd.

Pereira, L. S. 1999. Higher performance through combined improvements in irrigation methods and scheduling: A discussion. *Agricultural Water Management* 40 (2-3): 153-69.

Pereira, L. S., T. Oweis, and A. Zairi. 2002. Irrigation management under water scarcity. *Agricultural Water Management* 57 (3): 175-206.

Playán, E., and L. Mateos. 2006. Modernization and optimization of irrigation systems to increase water productivity. *Agricultural Water Management* 80 (1-3): 100-16.

Postel, S. 1999. *Pillar of sand: Can the irrigation miracle last?*. New York, United States: W.W. Norton.

Prajamwong, S., G. P. Merkley and R.G. Allen. 1997. Decision support model for irrigation water management. *Journal of Irrigation & Drainage Engineering* 123 (2): 106.

Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* 100 : 81-92.

Quiroga, S., Z. Fernandez-Haddad, and A. Iglesias. 2011. Crop yields response to water pressures in the Ebro Basin in Spain: Risk and water policy implications. *Hydrology and Earth System Sciences* 15 (2): 505-18.

Raes, D., S. Geerts, E. Kipkorir, J. Wellens, and A. Sahli. 2006. Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agricultural Water Management* 81 (3): 335-57.

Raes, D., P. Steduto, T. C. Hsiao, and E. Fereres. 2009. AquaCrop-the FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal* 101 (3): 438-47.

Shangguan, Z., M. Shao, R. Horton, T. Lei, L. Qin, and J. Ma. 2002. A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications. *Agricultural Water Management* 52 (2): 139-54.

Smith, M. 1992. CROPWAT: A computer program for irrigation planning and management. *FAO Irrigation and Drainage Paper* Number 46. Rome: FAO.

Smith, M., D. Kivumbi, and L. K. Heng. 2002. Use of the FAO CROPWAT model in deficit irrigation studies. In *Deficit irrigation practices: Water report 22.*, 17-27. Rome: Food and Agriculture Organization of the United Nations.

Steduto, P., T. C. Hsiao, D. Raes, and E. Fereres. 2009. AquaCrop-the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal* 101 (3): 426-37.

Stewart, J. I., and R. M. Hagan. 1973. Functions to predict effects of crop water deficits. *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers* 99 : 421-39.

Stewart, J. I., R. E. Danielson, R. J. Hanks, E. B. Jackson, R. M. Hagan, W. O. Pruitt, W. T. Franklin, and J. P. Riley. 1977. *Optimizing crop production through control of water and salinity levels in the soil*. Logan, Utah: Utah Water Research Laboratory.

Suryavanshi, A. R., and J. M. Reddy. 1986. Optimal operation schedule of irrigation distribution systems. *Agricultural Water Management* 11 (1): 23-30.

Tolk, J. A., and T. A. Howell. 2008. Field water supply: Yield relationships of grain sorghum grown in three USA southern great plains soils. *Agricultural Water Management* 95 (12): 1303-13.

Turral, H., M. Svendsen, and J. M. Faures. 2010. Investing in irrigation: Reviewing the past and looking to the future. *Agricultural Water Management* 97 (4): 551-60.

Western Irrigation District. 2012. *Western irrigation district: Where water is life*. http://www.wid.net/ (Accessed March 12, 2012).

Wichelns, D. 2002. An economic perspective on the potential gains from improvements in irrigation water management. *Agricultural Water Management* 52 (3): 233-48.

Yamashita, S., and W. R. Walker. 1994. Command area water demands. I: Validation and calibration of UCA model. *Journal of Irrigation and Drainage Engineering* 120 (6): 1025-42.

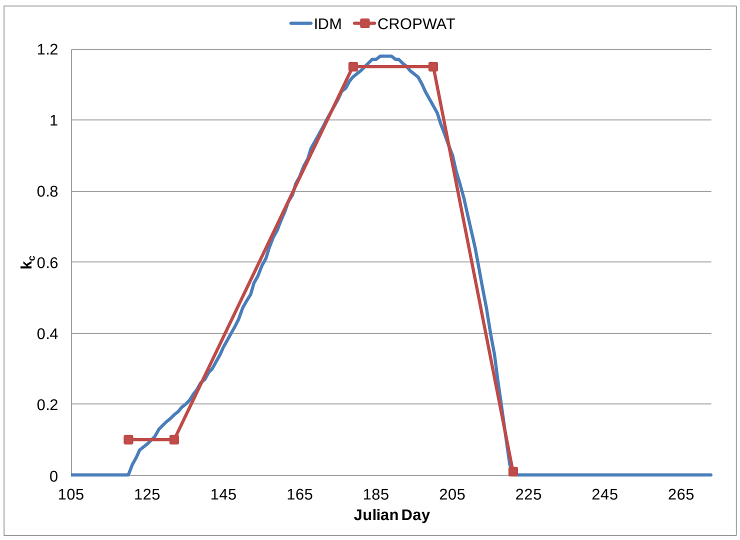
Zhang, B., F. Li, G. Huang, Z. Cheng, and Y. Zhang. 2006. Yield performance of spring wheat improved by regulated deficit irrigation in an arid area. *Agricultural Water Management* 79 (1): 28-42.

Zwart, S. J., and W. G. M. Bastiaanssen. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management* 69 (2): 115-33.

Appendix A - Crop data used in CROPWAT simulations

Crop Name: Barley   Planting date: 30/04   Harvest: 08/08

Stage		initial	develop	mid		late	total	
Length (days)	12		47		21		21	101
Kc Values		0.10		-->		1.15		0.01
Rooting depth (m)	1.20		-->		1.20		1.20	
Critical depletion	0.50		-->		0.50		0.50	
Yield response f.	0.20		0.60		0.50		0.40	1.15
Cropheight (m)					1.00			



Crop Name: Wheat Planting date: 30/04 Harvest: 22/08

Stage		initial	develop	mid		late	total	
Length (days)	8		52		30		25	115
Kc Values		0.05		-->		1.15		0.01
Rooting depth (m)	0.15		-->		1.00		1.00	
Critical depletion	0.50		-->		0.50		0.50	
Yield response f.	0.40		0.60		0.80		0.40	1.15
Cropheight (m)					1.00