Reservoir Management for Sustainable Irrigation in Alberta

by

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Abstract

Sustainable reservoir management is essential to ensure the productivity of agriculture and to adapt to a changing climate. This research firstly analyzes reservoir managers' perspectives in Alberta's heavily-allocated South Saskatchewan River Basin by applying a qualitative survey methodology in order to improve understanding of the behaviour of reservoir operators under various climatic and hydrological conditions. The data collected through interviews with water managers suggest that the current approach to reservoir operation in Alberta is oriented toward basin-scale cooperation, day-by-day release strategies, and early-season water rationing.

Furthermore, the research evaluates the possible impact on the water supply available in the Bow River Basin of alternative reservoir management strategies applied in the Bow River Irrigation District through the use of the Water Resources Management Model (WRMM) of the Government of Alberta. In particular, modified reservoir operations may permit the district to lower its total water deficit in dry years compared to the original version of the WRMM. However, the values of risk measures for water deficits, the water available for other irrigation districts, the Master Apportionment Agreement with Saskatchewan and the diversion rate from the Bow River are only marginally affected.

Finally, bounding scenarios of low and high irrigation demands for the three irrigation districts of the Bow River Basin (the WID, BRID and EID) and the Lethbridge Northern Irrigation District (LNID) of the Oldman River Basin were produced using the Government of Alberta's Irrigation Demand Model for a planning horizon extending to the year 2040. The water-use scenarios were applied to the WRMM to permit quantification of the water supply limits under dry to wet conditions from the historical period-of-record. There are no foreseen risks associated with the reference water-use and the low water-use scenarios for any of the four irrigation districts. However, the high water-use scenario is not sustainable for both the LNID and the WID in terms of risk measures based on water deficits and adherence to the Master Apportionment Agreement.

Preface

This thesis is an original work by Marie-Ève Jean. The interviews with water managers of southern Alberta, for which this thesis presents results, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Reservoir management for sustainable irrigation in Alberta", No. Pro00049354, August 7th, 2014.

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Finally, I would like to express my sincere gratitude to the love of my life, Charles, my family and close friends for their support and encouragement to overcome the doubts and difficulties I occasionally faced, but more particularly, to share the successes and joy of this journey as well as spending some amazing time discovering the beautiful landscapes of western Canada.

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List of Abbreviations and Symbols

Acronym	Definition
AAF	Alberta Agriculture and Forestry, formerly called Alberta Agriculture and Rural Development (AARD)
AEP	Alberta Environment and Parks, formerly called Alberta Environment and Sustainable Resources Development (AESRD) and Alberta Environment (AENV)
BRID	Bow River Irrigation District
EID	Eastern Irrigation District
ESO	Explicit Stochastic Optimization; a mathematical programming technique formulated to operate directly on probabilistic descriptions of random variables
ET_0	Reference evapotranspiration; the evapotranspirative rate of a grass reference crop
ET_a	Actual crop evapotranspiration
IDM	Irrigation Demand Model
ISO	Implicit Stochastic Optimization; a deterministic mathematical programming technique formulated to optimize over a continuous series of historical or synthetically generated variables time-series
K_c	Crop Coefficient; percentage of evapotranspiration that is satisfied by a combination of rainfall and irrigation due to management practices in the field
K_s	Evapotranspiration Scaling Factor; a dimensionless parameter which refers to all the specific crop characteristics affecting its evapotranspiration rate such as the type of crop or the growing stage
LNID	Lethbridge Northern Irrigation District
SSRB	South Saskatchewan River Basin
WID	Western Irrigation District
WRMM	Water Resources Management Model

1. Introduction

1.1 Irrigation in Alberta

In southern Alberta, numerous dams are operated to meet irrigation requirements, the largest water-use in the Province. In fact, irrigation water-use accounts for 60-65% of Alberta's annual water consumption, and represents a surface water allocation volume of more than 4.2 billion cubic meters (AESRD 2014). Despite its high consumptive use of water, irrigation is essential to the economy, as it enhances agricultural reliability and productivity in the otherwise dry region of southern Alberta. Indeed, irrigated agriculture can increase dryland farming yields in Alberta by 250 to 300% (IWMSC 2002a) and provides even greater economic benefits during drought years (Samarawickrema & Kulshreshtha 2008). Irrigated lands in Alberta represent two-thirds of Canada's irrigation development (AAFRD 2004) and contribute almost 20% of the Canadian agri-food export (Alberta Canada, 2014). Irrigation infrastructure also provides wildlife habitat, recreational parks and enhances the well-being of rural communities (AARD 2014a). From a broader perspective, irrigation is essential to meet global food demand as irrigated lands cover only 16% of the arable land cultivated globally but produce 44% of the total crop production (Alexandratos & Bruinsma 2012). With the global population projected to reach about 9.5 billion by 2050 (UNESA 2012), the need for irrigation will only increase.

1.2 Irrigation Challenges

Over the near- to medium-term, irrigation in Alberta and in many places of the world is facing the necessity to be more efficient, productive, profitable and sustainable in order to cope with socio-economic growth, climate change impacts and ecological concerns (Lenton 2014; Martz *et al.* 2007). Indeed, irrigation development in Alberta takes place mainly in the South Saskatchewan River Basin (SSRB), where the water supply is highly variable and where the Province's population is concentrated (SWSSSC 2010). From a 2013 population of nearly 4.0 million, Alberta's population may grow to more than 6.2 million in 2041, according to the medium scenario of Alberta Treasury Board and Finances (2014). Moreover, the potential impact of climate change in the SSRB suggests a net decrease in surface water yield during summer (Rood *et al.* 2008; Schneider 2013; Tenzeeba & Gan 2012) while a warmer climate will result in a lengthening of the growing season and more evaporative losses (Barrow & Yu 2005). From a water management point-of-view, these changes translate into a lower water supply and higher water demand, producing greater pressure on watershed resources. Climate change studies also predict a shift of the spring snow melt runoff to earlier in spring (Rood *et al.* 2008; Tenzeeba & Gan 2012), which may affect reservoir refill and drawdown schedules. These environmental and socio-economic changes must drive efforts to adapt current water resources management practices to ensure a safe and sustainable water supply for the environment, economy and society.

1.3 The "Water for Life" Strategy of the Government of Alberta

In 2003, Alberta introduced a water management strategy, *Water for Life*, in order to respond to the pressures on its water resources (Alberta Environment 2003a). In 2006, the SSRB Water Management Plan developed by Alberta Environment and Parks (AEP) led to the establishment of Water Conservation Objectives, which specified new minimum environmental flow requirements and restricted the use of unallocated water to conservation, storage or First Nations projects for the Bow, Oldman and South Saskatchewan Sub-basins (SWSSSC 2010). Since 2006, these sub-basins have been closed to any further water allocation, which reinforces the need to improve water-use efficiency, particularly in the irrigation sector as it accounts for the greatest water-use. Similarly, Alberta Agriculture and Forestry (AAF) established a complementary strategy that aims to increase the productivity, efficiency, conservation, water supply and environmental stewardship of the irrigation industry (AARD 2014a).

1.4 Reservoir Management Approaches

Reservoir operations need to be optimized to enhance the productivity of irrigated agriculture, while ensuring the environmental integrity of water resource systems (Ahmad *et al.* 2014; Loucks 2000). Indeed, the aim of water resources management studies is to maximise the beneficial use of water in existing reservoir systems (Labadie 2004).

Since the early 'Sixties, various water resources models and optimization approaches have been developed to improve water management in complex river systems (Labadie 2004). The simplest optimization method used in river basin modelling studies is called Single Time-step Optimization (STO) because it finds optimal water allocations throughout a river basin at each simulated time-step without considering future release decisions (future water deficits, for example) or incoming runoff. STO's utility is therefore limited, as there is no guarantee that the model will reach optimality. In contrast, the Multiple Time-step Optimization (MTO) approach, which aims to derive optimal reservoir operations based on perfect foreknowledge of water supply and water demand over the entire simulation cycle (typically a single irrigation season), is seen as a promising tool to compensate for STO weaknesses. However, the MTO formulation involves a deterministic description of all simulated variables, which does not capture the inherent stochastic nature of the hydrological processes. The applicability of MTO-based modelling in real-life operations remains a challenge as no universally-accepted methodology has been developed for the analysis and implementation of the optimization results (Ilich 2011; Labadie 2004).

Furthermore, despite progress in reservoir modelling and management with the improvement of computer capabilities and the development of optimization methods, decision-makers and reservoir managers tend to resist application of the output of computer-based optimization and simulation models to real-world reservoir operations (Black *et al.* 2014, Hejazi *et al.* 2008, Labadie 2004, Loucks & van Beek 2005, Simonovic 1992, Toebes & Ruvikchai 1978; Wurbs 1993; Yeh 1985). As emphasized by Labadie (2004), the incorporation of optimization tools into decision-support systems, which involves reservoir managers' judgement in the use of model simulations, helped partially bridge the gap between theory and practice. A further understanding of current water managers' perspectives on reservoir operations could help to overcome the remaining implementation limitations of theoretical optimization outputs. As a result, innovative advances in water resources management would not be limited to theoretical applications.

1.5 Previous Studies

The research follows three previous projects that were components of a larger study titled "Water: Making do with what we have", led by Drs. Henning Bjornlund and Kurt Klein of the University of Lethbridge. They aimed to identify potential avenues for water savings in the Western Irrigation District (WID), one of the three irrigation districts located in the Bow River Basin. The WID, located just east of Calgary, is the closest district to a large urban area and has a small water storage capacity compared to the other districts that divert water from the Bow River Basin (AARD 2014b). The district's infrastructure is also spread out over a large area, making it challenging to maintain. The first study, by Khan (2011), described WID's current water management practices and its conveyance system, as well as possible alternatives to improve the district's water-use efficiency. A second study conducted by González (2012) evaluated the district's crop yield under reduced on-farm water application and assessed the possible water savings obtained from the conveyance system rehabilitation using the IDM. Finally, a third study completed by Huggard (2014) investigated the impact of additional water storage and different optimization techniques on WID's reservoirs management using the WRMM. More particularly, various versions of the WRMM were compared: the original WRMM, the WRMM-Decision Support System, and the Distributed Deficit Water Resource Management Model developed by Optimal Solutions Ltd (Calgary, Alberta).

1.6 Research Objectives

This research is part of a multi-disciplinary project supported by the Alberta Land Institute (ALI) that aims to develop a systems-based decision-support tool for policymakers assessing a potential expansion of the irrigation sector to 2040, given changes in reservoir management, irrigated areas, crop types, technology, and regional population and other economic drivers.

The main objective of this research is thus to contribute to the ALI work by understanding and improving reservoir management strategies for sustainable development of the irrigation sector. This objective can be divided in three more specific and interconnected goals:

1. Improve understanding of the behaviour of reservoir operators and how closely it is related to optimization modelling theory;
2. Address whether the water supply available for irrigation in the Bow River Basin could be increased by improving reservoir management;
3. Assess the risks and trade-offs associated with irrigation sector development under bounding irrigation-demand scenarios envisioned for 2040 in the Bow River Basin area.

To address the three goals required three interrelated methodological steps:

1. Analysis of the basis of reservoir managers' operational decisions under different hydrological conditions by conducting qualitative interviews with water managers from the main irrigation districts in Alberta and from governmental institutions;
2. Evaluation of the possible impact on the water supply available for the three irrigation districts of the Bow River Basin and the Lethbridge Northern Irrigation District (LNID) of the Oldman River Basin of alternative reservoir management strategies applied in the Bow River Irrigation District (BRID) through the use of the Alberta Environment and Parks (AEP)'s Water Resources Management Model (WRMM);
3. Determination of the available water supply for the three irrigation districts of the Bow River Basin and the LNID under bounding scenarios of irrigation demands for dry to wet conditions. The use of the Irrigation Demand Model (IDM) of Alberta Agriculture and Forestry (AAF) in conjunction with the WRMM of AEP permits simulation of the water demand and supply for a series of historical hydrological and meteorological data.

The Figure 1 presents schematically the three research steps to address the overall research objective and their interconnections.

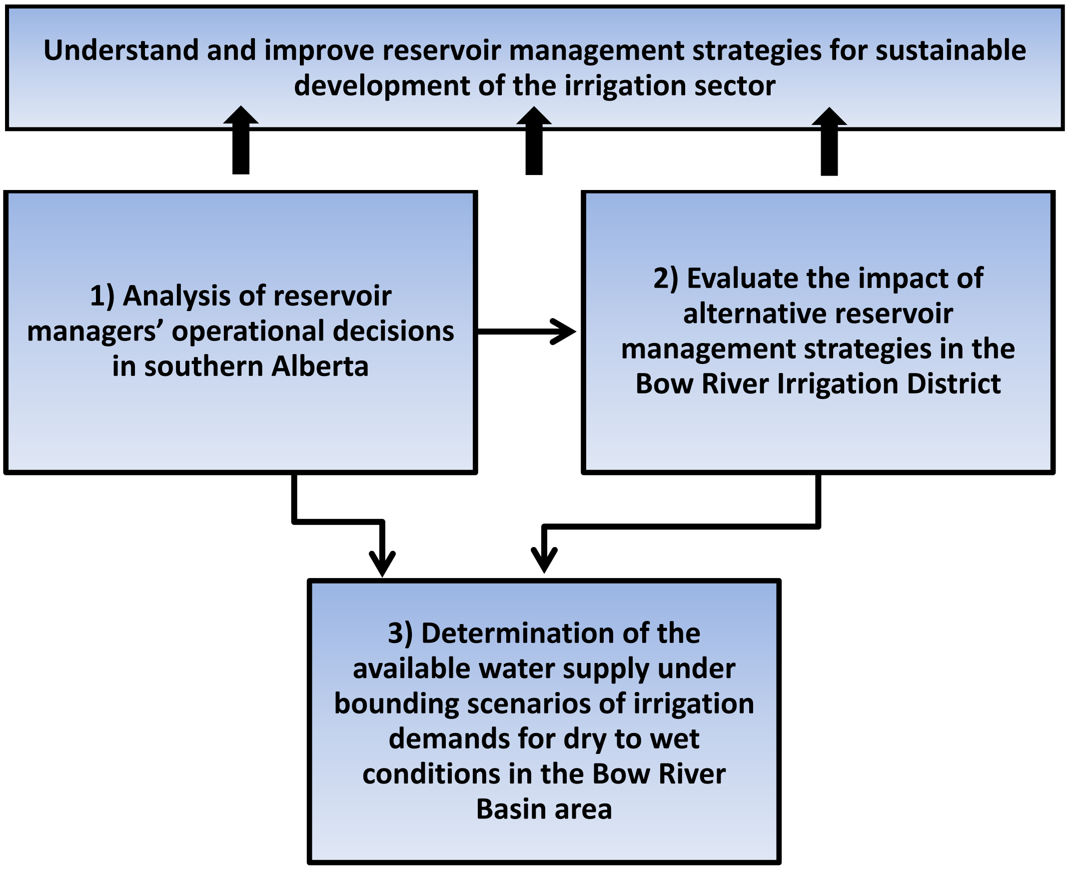


Figure 1: Research steps process

To achieve the first goal, the study focuses on reservoir managers' perspectives and their similarities to and differences from optimization modelling approaches in the SSRB, Alberta's most heavily-allocated river basin. The aim is to assess how the behaviour of reservoir optimization models could be revised to represent better the decision-making processes of water managers, such as the data they rely on and the manner in which they make decisions, and ultimately, to provide improved computer tools for irrigation district management.

Second, the thesis evaluates the effects of alternative reservoir management strategies on basin-level water availability. This second step is directly dependant on the first objective, as the interview data on current reservoir managers' operational decisions guided the development through modelling of reservoir management strategies that could potentially increase the water supply available for irrigation. The WRMM is applied to the Bow River Basin, one of the SSRB sub-basins, for this purpose. The focus is on the BRID, which is the district located downstream of the WID and upstream of the Eastern Irrigation District (EID), since it is logical to assess the reservoir management options from upstream to downstream in the Bow River Basin, and BRID was the next irrigation district following the WID in Huggard's (2014) study. Moreover, in contrast with the previous WID modelling studies, the research presented here analyses the impact of different scenarios of reservoir management for the entire Bow River Basin, rather than for a particular district. Indeed, consultations with AEP and AAF indicated that the interconnection of the three irrigation districts in the Bow River Basin – the WID, the BRID, and the EID – is critical to consider when evaluating the effects of management changes in individual districts. Moreover, as the simulation model used for this study simulates the water diversions of the Lethbridge Northern Irrigation District (LNID), located in the Oldman River Basin, the research considered the performance of this district as well.

The third step of the research is also linked with the first and second goals of the thesis. Indeed, the interview work permitted the collection of data on future irrigation expansion plans envisioned by the districts and the current average irrigation demands. In addition, the simulation work of step two leads to the identification of reservoir management strategies that could increase the water supply available for irrigation purpose in the Bow River Basin. These scenarios are then used to establish the water supply limits under plausible minimum and maximum irrigation demand scenarios for the next 25 years (2040). This analysis is done through modelling of the water demand and supply for the same four irrigation districts previously mentioned: the WID, BRID, EID and LNID, under dry to wet conditions – essential information for assessing the risks and trade-offs associated with irrigation sector management strategies.

The simulation work involved in the second and third steps of the research uses two existing water resources simulation models: the IDM, which is used to produce water demands under different crop mixes and scenarios of irrigation development, and the WRMM, which estimates the available water supply for irrigation in the Bow River Basin under different reservoir management strategies, hydrological conditions and water demand levels.

1.7 Thesis Chapters

The thesis provides background information on the irrigation system in Alberta, the Bow River Basin and the irrigation districts in Chapter 2. The literature review of water resources modelling approaches, optimization techniques and research gaps is presented in Chapter 3. Next, Chapter 4 describes the methodology and introduces the results of the interviews conducted with water managers in order to address the first objective of the research project. Chapter 5 reviews the methodology of the simulation tools and presents the results and discussion of the simulation work that addresses the second and third objectives of the thesis. Finally, Chapter 6 concludes the thesis and presents recommendations.

2. Background

2.1 Irrigation legislation and history in Alberta

The development of irrigation in southern Alberta is characterized by the legislation adopted over time and the historical context in which it was developed. In western Canada, the "Riparian Rights Doctrine" was the first legislation determining water-uses. This doctrine allowed landowners adjacent to a stream to divert water as long as their water withdrawals were not deteriorating the natural flows in terms of quantity and quality. In a water-scarce region such as southern Alberta, the riparian rights impeded large irrigation projects because they were too constraining on water diversions (AMEC 2009a). In 1894, the "Northwest Irrigation Act" was therefore adopted by the Dominion Parliament in order to encourage settlement of communities by facilitating irrigation. Since then, water allocations have been governed by the "first-in-time, first-in-right (FITFIR)" or "seniority rule" principle. This system allows water withdrawals given the priority of supply established by the date at which a water license was issued. When the federal government transferred to the Province of Alberta the responsibility for managing water on its territory, legislation similar to the "Northwest Irrigation Act" was adopted in 1931 and called "Alberta's Water Resources Act". Most recently in 1999, Alberta's legislation was modified and called the "Water Act". According to the current legislation, senior licensees have the right to divert their full allocated volume of water before junior licensees divert any amount. However, if the allocated volume is greater than the licensee's capacity to divert water, the user's right to water becomes limited to the volume and the rate his conveyance system is capable of carrying (Province of Alberta 2011). Finally, while maintaining the FITFIR principle, the "Water Act" also includes new approaches for application in times of water scarcity (SWSSSC 2010).

Water licenses are necessary to divert any amount of water, as defined in the "Water Act". More particularly, the licence identifies the water source, the diversion site, an estimation of consumptive losses and return flows as well as the maximum flow rate for the diversion, which usually depends on the river stage (Alberta Environment 2006). The annual permissible diversion of water is estimated as the license allocation plus the return flows. Annual water-use is often less than the licenced amount and varies considerably from one year to another as a consequence of the weather, crop patterns, and economic factors (SWSSSC 2010).

Note that some small water-uses, such as domestic or non-irrigated agriculture activities, do not require formal water licenses. In times of water shortage, these water-uses have the highest priority, which means they should not be restricted (SWSSSC 2010). Moreover, in 2011, the 13 Irrigation

Districts commonly agreed to ensure water supply for human uses in periods of water scarcity (Canada Newswire 2011). This agreement aims to protect the water needs of communities even if they hold junior licences, while maintaining the old “seniority rule” principle for the remaining amount of water.

The province of Alberta is also subject to transboundary water legislation, which defines agreements for water sharing with the neighbouring provinces and territories of Canada as well as the United States. Of interest for this research project is the “Master Agreement on Apportionment” established in 1969 for the South Saskatchewan River as it passes through the provinces of Alberta and Saskatchewan, which requires Alberta to pass one-half of the South Saskatchewan natural flow at the province’s boundary to Saskatchewan each year. It is important to note that there is no policy on how much each sub-basin of the South Saskatchewan River must contribute to the Apportionment Agreement (Alberta Environment 2006). Historically, an average value of 81% of the natural flow has passed through Alberta to Saskatchewan (SWSSSC 2010).

Over the years, irrigation development in Alberta was also influenced by the different entities that took responsibility for the management of irrigation projects. In the early 20th century, irrigation projects were undertaken by private enterprises such as the Canadian Pacific Railway and individual land owners. At that time, it was financially difficult to extend and maintain irrigation infrastructure. As an alternative to privately own projects, irrigation co-operatives formed by irrigators proved to be a more efficient and economical solution, and were therefore authorized under the “Irrigation District Act” in 1915. Private entities were then gradually replaced by irrigation districts and, by 1968, all thirteen irrigation districts were operating (IWMSC 2002a). Figure 2 presents where each irrigation district is located in Alberta.

Operation of large-scale irrigation projects also requires maintenance of the irrigation network. Currently, each irrigation district possesses the infrastructure used to distribute water within its boundaries, while the irrigation headworks, such as weirs and on-stream reservoirs, are owned and managed by the Government of Alberta for eleven irrigation districts (AMEC 2009a).

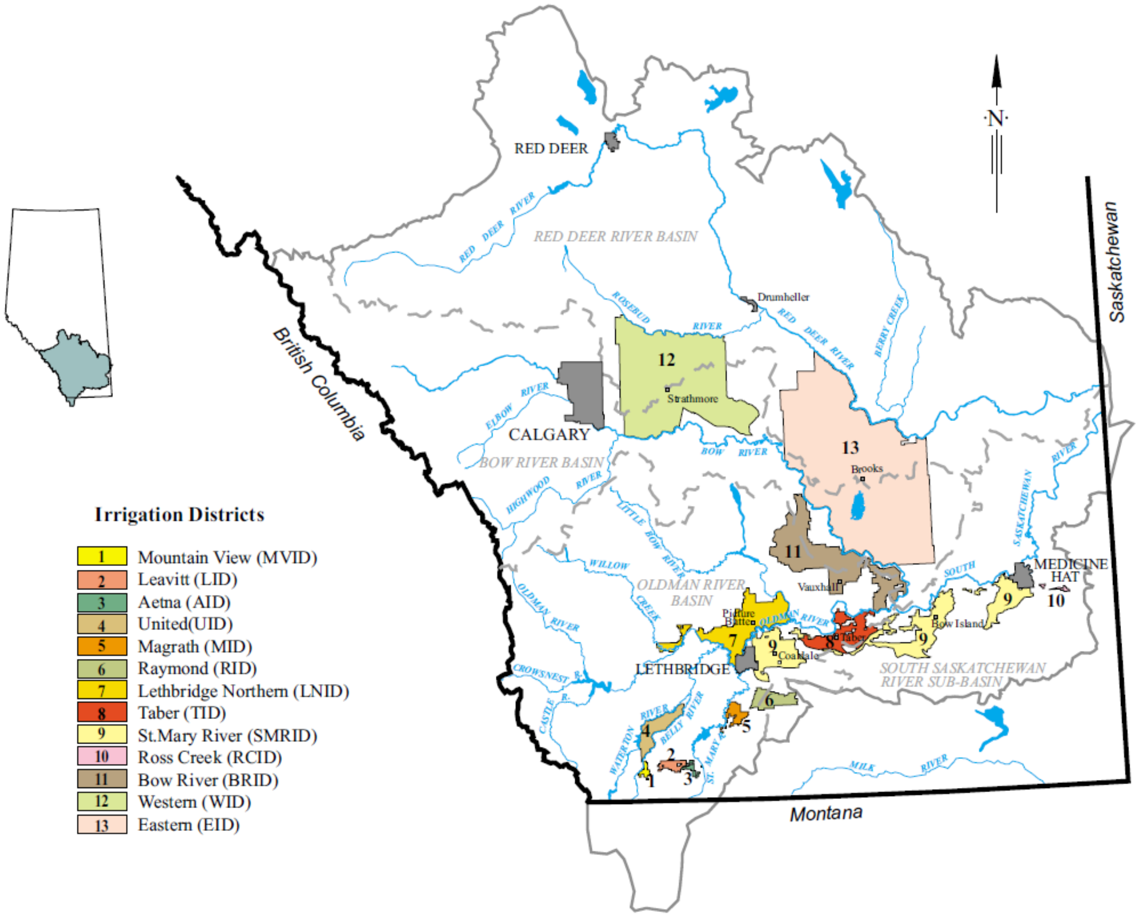


Figure 2: The Thirteen Irrigation Districts in Southern Alberta (IWMSC 2002a: xi)

2.2 Bow River Basin

The research project addresses the impact of different scenarios of irrigation development and reservoir management for the irrigation districts of the Bow River Basin. As shown by Figure 3, the Bow River flows from the Rocky Mountains on the west side of the Province toward Saskatchewan on the east side and includes a gross drainage area of about 25,300 square kilometers (SWSSSC 2010). It meets the Oldman River south-east of the town of Vauxhall to become the South Saskatchewan River.

As the largest tributary of the South Saskatchewan River, the Bow River contributes almost 43% of the average annual flow, or about 3.8 billion cubic meters from the total of 8.8 billion cubic meters (SWSSSC 2010). The Bow River is a snowmelt dominated river with the upstream Rocky Mountain snowpack contributing to about 80% of the total river flows. Its yearly hydrograph is characterized by a peak discharge in June, followed by a series of minor and broader peak flows, all corresponding to the progressive melting of the snowpack accumulations from low to high elevations (Bow River Basin Council 2010b). The snowpack values vary from one year to another in a historical dataset that records 25 to 37 years of data for 20 stations. As reported by AEP (2015b), the difference from the highest snow water equivalent values to the lowest values measured in June for the same station varied from 270 to 920 millimetres (mm). In terms of precipitation amounts, the Bow River Basin average total annual precipitation is about 538 mm for the entire basin (AMEC 2009a: 12), but varies from 270 mm in the Grass Land natural region to 930 mm in the Rocky Mountains natural region (AMEC 2009a: 6).

Bow River winter flows are generally low, and the lowest flows take place in January. In winter, groundwater could contribute to 20% of the total flow and glacial melt constitutes about 2.5% of the total during summer and fall. However, glacial contributions could represent a greater ratio in dry years and particularly in summer (Bennett & Murray 2010). Seasonal river flow variations are important as shown by Figure 4 for the Bow River historical flows at Calgary gauging station. The Bow River peak runoff at the mouth can reach as much as 1,200 cubic meters per second in June and its low flows can be reduced to as low as 5 cubic meters per second in mid-winter (AEP 2015a). Bow River flows are also characterized by a moderate inter-annual variability compared to its neighbouring rivers (Red Deer River or the Oldman River) due to the upstream reservoir regulations in winter for hydropower generation (AMEC 2009a). The inter-annual variability of the historical flows is indicated in Figure 4 by the difference between the lower and upper quartiles. Furthermore, the seasonal river flow volume (from April to October months), which is of major importance for irrigation diversions, was on average 2,216,000 cubic decameters (dam^3), but has reached a maximum of 3,779,000 dam^3 and a minimum of 1,299,000 dam^3 at the Calgary gauging station (05BH004) (values calculated from data of the Water Survey of Canada 2014).

Bow River runoff from the mountains is essential for irrigation, hydropower or municipal uses, whereas the plains area runoff contributes greatly to the soil moisture and local water storage facilities. Indeed, although snowpack accumulation in the upstream Rocky Mountains is the major factor contributing to Bow River runoff, the rainfall that occurs during the irrigation season over the entire river basin area as well as the soil moisture state all affect the hydrological conditions of the watershed (AEP 2015b). Based on the multiple combinations of factors, it is hard to develop specific criteria to differentiate typical dry to wet climate conditions. To classify conditions as "dry", the Canadian Drought Monitoring program uses precipitation, temperature, drought model index maps, and climate data to develop monthly map showing drought severity under a five-class system based on the percentile chance of occurrence from the historical period-of-record (Agriculture and Agri-Food Canada 2015). As another example, Alberta Environment and Parks (2015b) and the United States Department of Agriculture (cited by Washington State Department of Ecology 2015) characterize hydrological and meteorological data as representative of average, dry or wet conditions. According to their method, a datum is considered representative of normal conditions if it falls in the “normal range” of data, which is delimited by the lower and upper quartiles of the historical dataset. In other words, normal values correspond to 75 to 125% of the mean value of the dataset. Moreover, dry conditions define hydrological and meteorological data that are below the lower quartile of the historical dataset (<25%) and wet conditions describe values above the upper quartile (>75%). In terms of river flows, the upper quartile of the seasonal runoff volume from April to October at the Calgary gauging station (05BH004) was 2,265,000 dam^3 and the lower quartile was 1,778,000 dam^3 for the 1911 to 2013 period (calculated from Water Survey of Canada 2014). The upper quartile of the monthly snowpack values in June for the station Sunshine Village reported by AEP (2015b) was 627 mm, whereas the lower quartile was 331 mm for the historical dataset lasting from 1982 to 2015. The Government of Alberta also classifies snowpack accumulations, river runoff forecast and average precipitation with a more detailed scale varying from much-below-normal, below-normal, normal, above-normal to much-above-normal in order to further differentiate the expected hydrological state of the river basin (AEP 2015b). Generally, climatic values further below or above average are more susceptible to lead to dry or wet conditions respectively, with the snowpack data having the dominant impact; however, the relative contributions of snowmelt-runoff and of seasonal precipitation in determining specifically a dry, normal or wet type of year have not been clearly established, and the intensity, duration and frequency of rainfall events, for example, should also be considered.

Three irrigation districts operate within the Bow River Basin and are identified in Figure 3: the Western Irrigation District (WID), the Bow River Irrigation District (BRID) and the Eastern Irrigation District (EID). The Bow River Basin has the highest population concentration in Alberta, with the City of Calgary along the Bow River banks. It is also considered the most regulated river in Alberta with its thirteen dams, four weirs, and eight reservoirs (Bennett & Murray 2010). AMEC (2009a) indicates that the annual average flow of water for the Bow River was about 70% of its naturalized flow for the period of 1992 to 2001 as a consequence of water withdrawals from irrigation districts. The naturalized flow is defined as the estimated river flow that would occur without any regulation from dams or other hydraulic infrastructures. In total, 60% to 70% of the Bow River annual flow volume is allocated through water licences with the majority of the volume serving irrigation purposes. Figure 5 compares the calculated mean naturalized flow with the actual mean flow at Calgary.

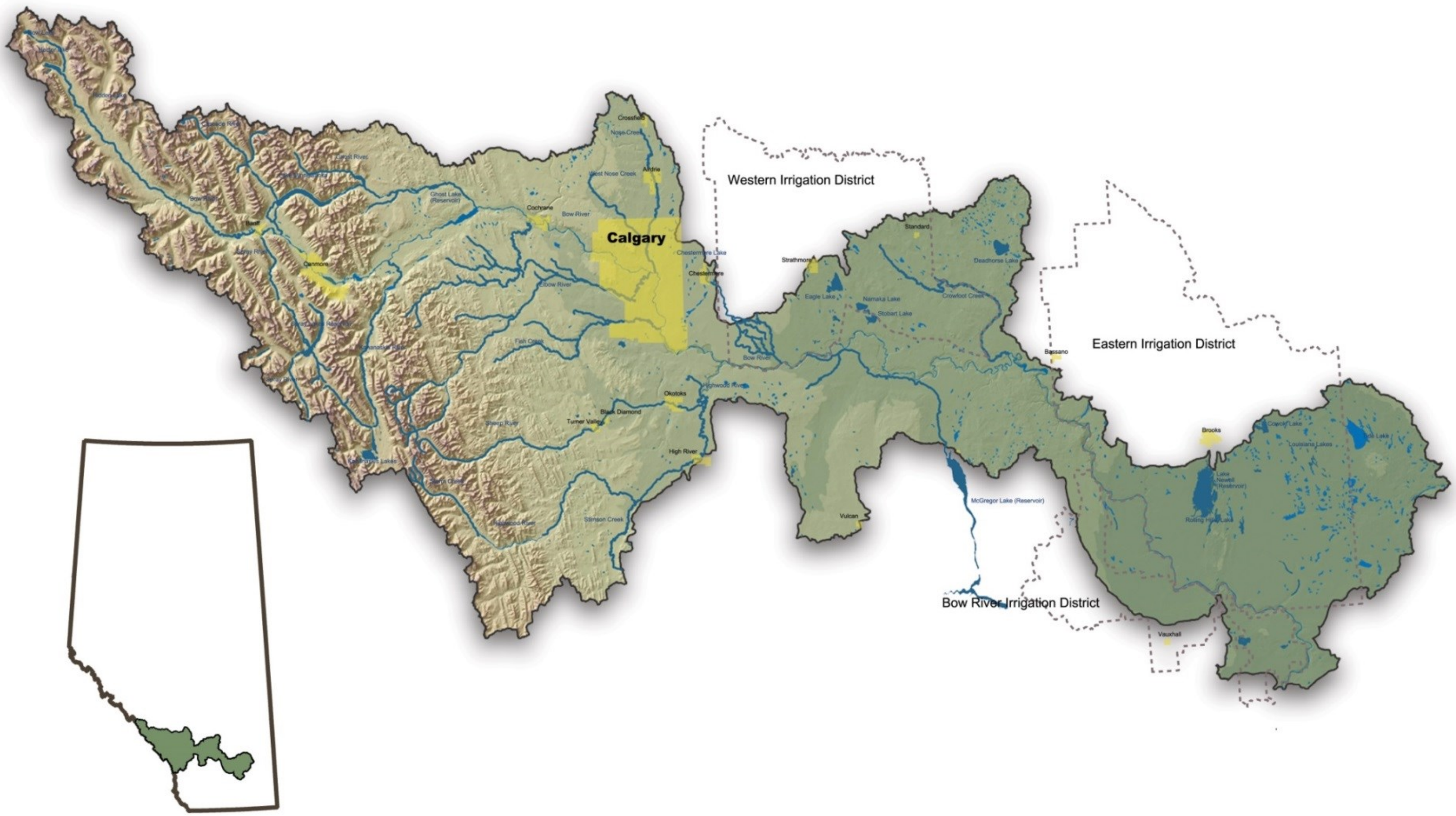


Figure 3: Map of the Bow River Basin (Bow River Basin Council 2010b)

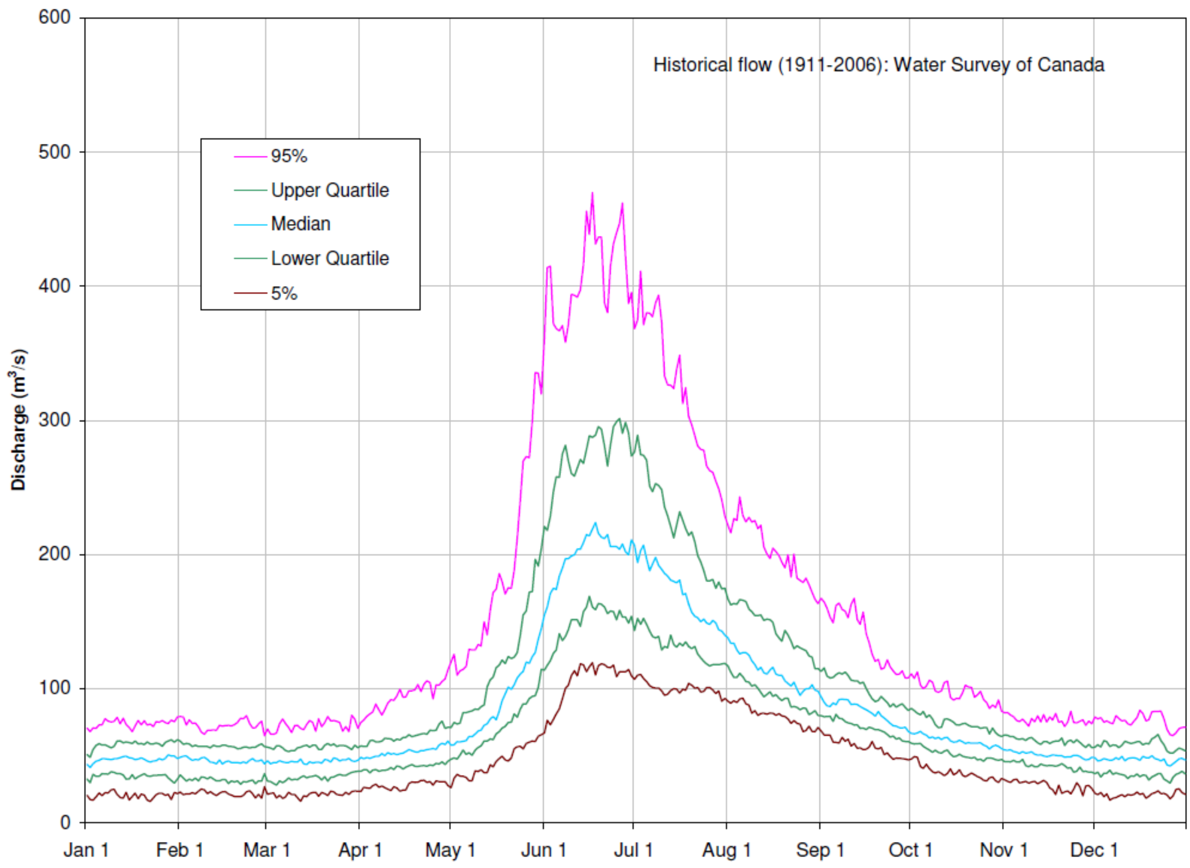


Figure 4: Bow River at Calgary Historical Discharge 1911-2006 (AMEC 2009b: 48)

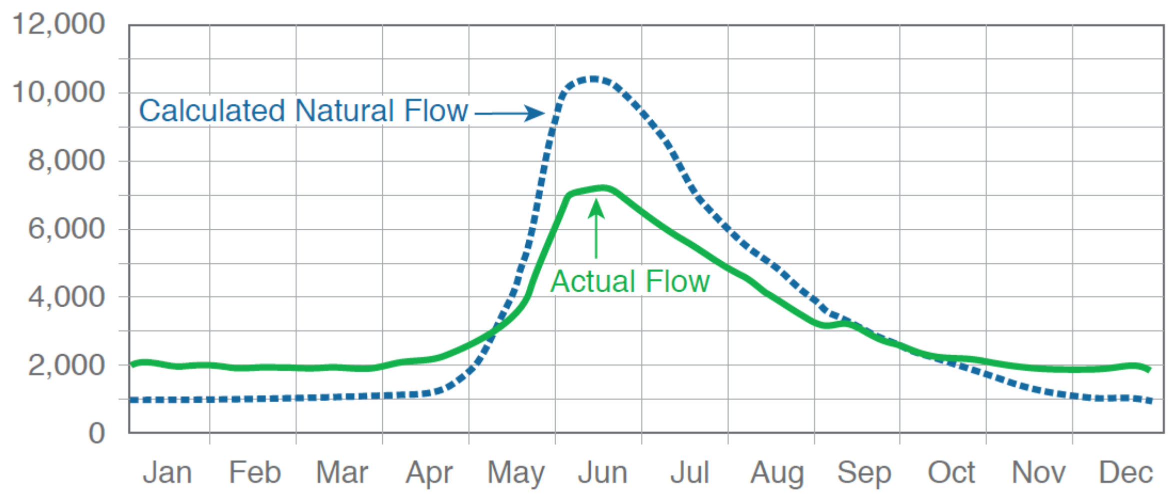


Figure 5: Bow River at Calgary, Natural and Actual Flow in cubic feet per second 1960-1997 (Bennett and Murray 2010: 3)

2.3 Irrigation Districts

2.3.1 Irrigation Districts Allocation and Assessed Acres

Collectively, the irrigation districts have a licenced surface water allocation of almost 3.5 billion cubic meters. However, their average gross annual diversion has been approximately 60% of their licence from 1981 to 2013 (Calculated from AARD 2014b). The gross diversion corresponds to all the water serving irrigation purposes but also municipal, domestic, agricultural, industrial and environmental uses and the filling of reservoirs. The diverted water has decreased over the last twenty years even though the irrigated land area has consistently increased. Indeed, Figure 6 shows the total assessed acres from 1970 to 2013, which have more than doubled over time, and Figure 7 provides an overview of the total gross diversion volume and the total water allocation for the thirteen irrigation districts from 1976 to 2012 (AARD 2014b).

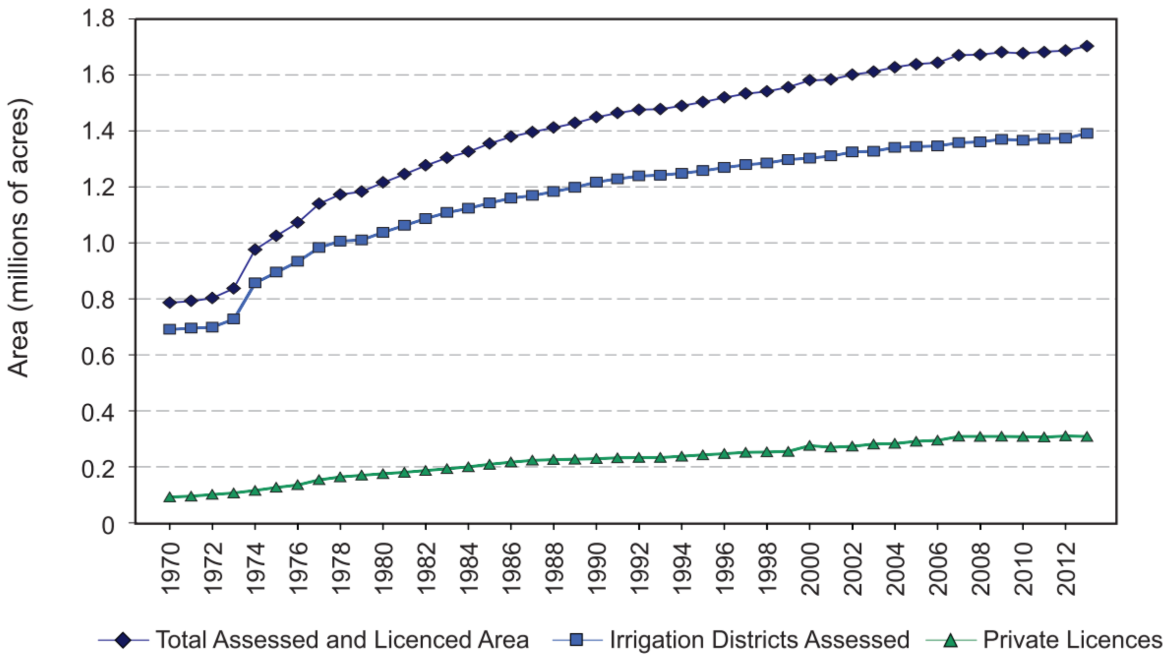


Figure 6: Thirteen Irrigation Districts Assessed Acres (AARD 2013b: 11)

The total assessed and licenced areas refer to the districts' expansion limit, which defines the maximum land area that can be irrigated. Irrigation district assessed acres are the land area recorded on the irrigation district assessment roll as possible irrigated land under the "Irrigation District Act". Therefore, the assessed acres are either less than or equal to the expansion limit of a district. The expansion limit can be further increased through a process established in the "Irrigation Districts Act" in 1999, which requires the approval of the irrigators by plebiscite (Government of Alberta 1999). The assessed acres have increased considerably since the early 1970s as Provincial

Government support has facilitated rehabilitation and expansion of the districts' conveyance infrastructure and irrigation headworks (IWMSCa 2002).

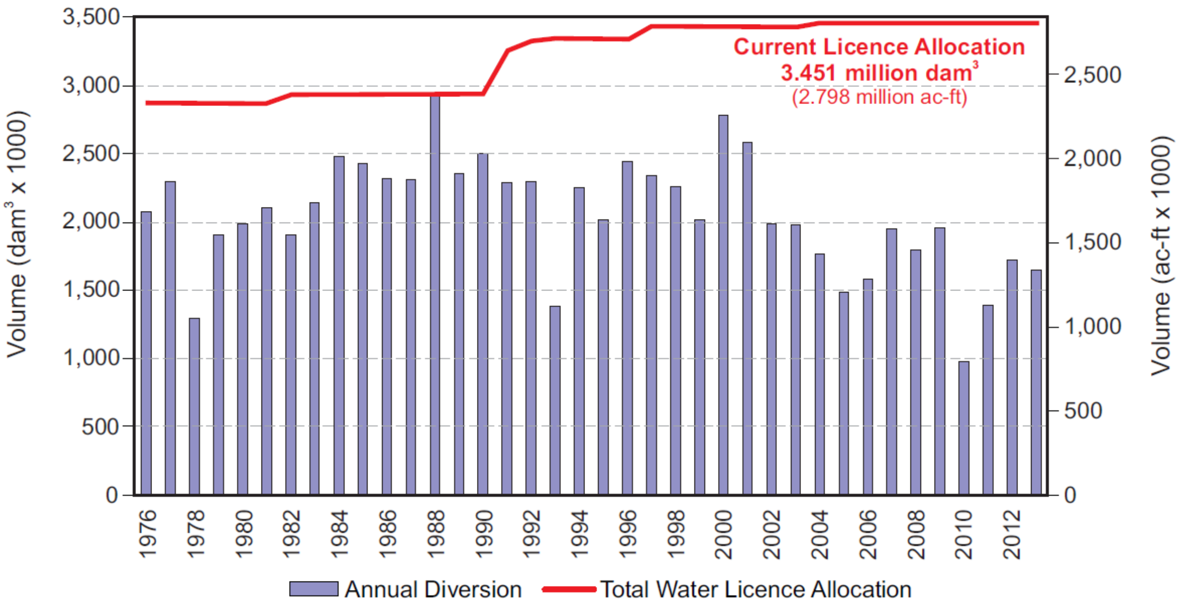


Figure 7: Thirteen Irrigation Districts Gross Diversion and Licence Allocation (AARD 2014b: 11)

Finally, the inter-annual variability of the gross irrigation volume is attributable to variable weather and hydrological conditions, while the recent decreasing trend is due to districts' conveyance infrastructure rehabilitation and on-farm improvement of irrigation system efficiency (AARD 2014a). The total licence allocation of about 3.5 billion cubic meters will probably remain close to its current value as since 2006 the Government has limited the use of unallocated water to conservation, storage or First Nations projects (WSSSC 2010).

2.3.2 Irrigation Districts Efficiency

In order to illustrate the improvement in water efficiency experienced by the irrigation sector, Figure 8 presents the shift over the last decades of on-farm irrigation methods, which have moved from surface irrigation to a majority of low pressure pivot systems. It was estimated that on-farm irrigation in Alberta has an average efficiency of 78% and could reach 85% in the future (AARD 2014a). Figure 9 shows how district infrastructure has improved over the past 15 years, with pipelines comprising almost half of the district conveyance network. The majority of the investment necessary to rehabilitate district infrastructure was provided by the Provincial Government through the Irrigation Rehabilitation Program of Agriculture and Rural Development (now called Agriculture and Forestry; Government of Alberta 2011).

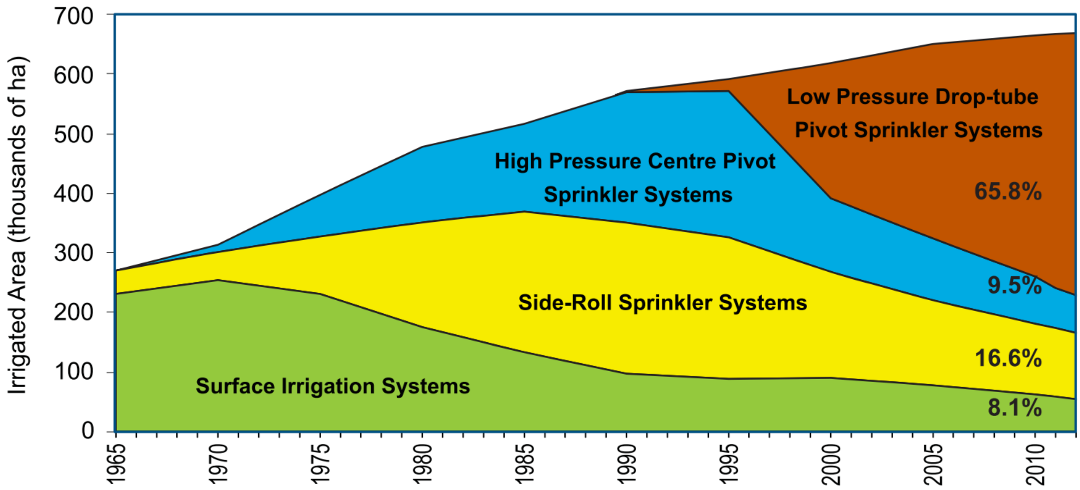


Figure 8: Irrigation Methods (AARD 2014: 8)

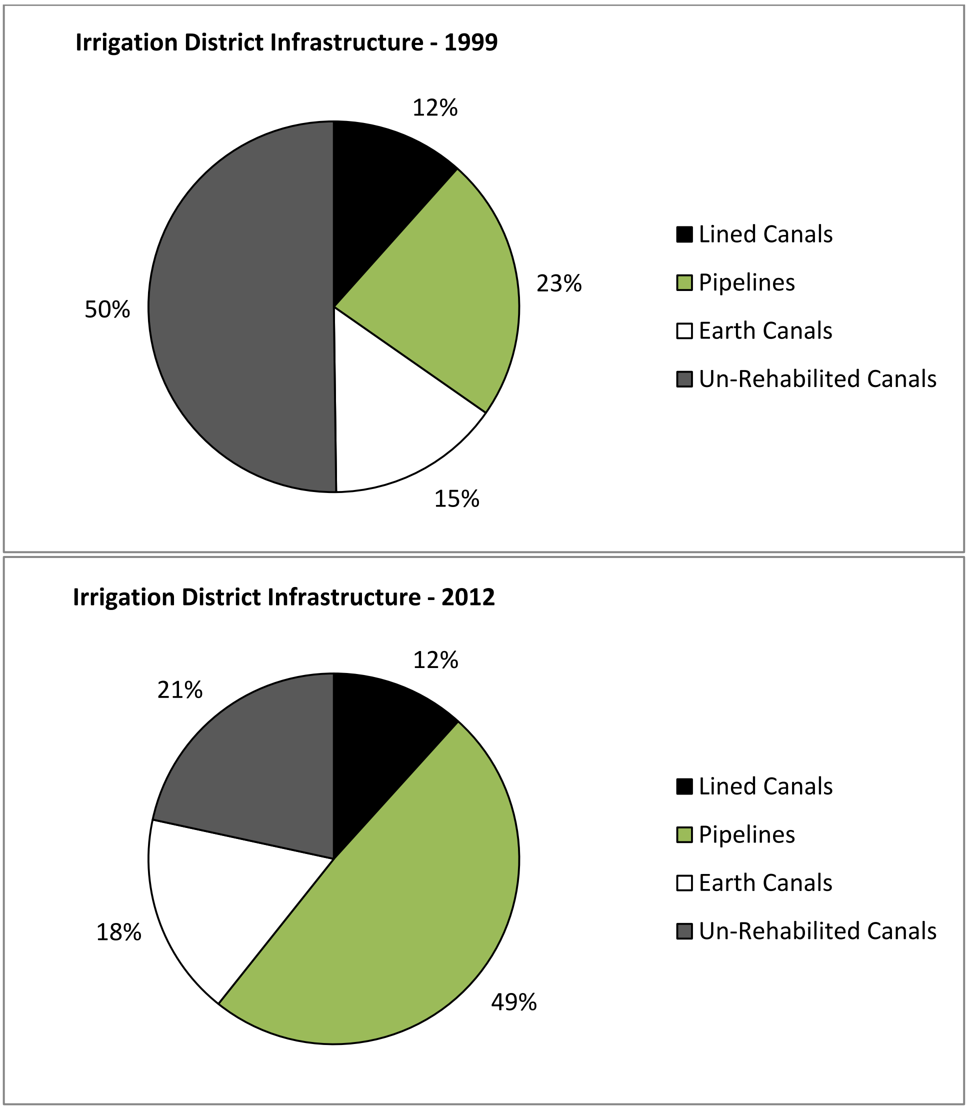


Figure 9: Irrigation Districts Infrastructure (Adapted from Bennett 2014: 14)

2.3.3 Crops grown in southern Alberta

Different types of crops are grown in the irrigation districts of southern Alberta than in dry land farms, as irrigation can broaden the varieties of crops available (IWMSC 2002a). Over time, the districts have diversified their production as more effective on-farm irrigation systems have replaced more labour-intensive and lower-efficiency systems. Market accessibility and agricultural activities taking place in each irrigation district area have also influenced the crop mix trends. Crops in Alberta are generally classified according to trade use, as cereals, forages, oil seeds, speciality crops and other – see Table 1 (AARD 2014b). Figure 10 illustrates the historical crop mix from 1974 to 2013 for the 13 irrigation districts together, with the land covered by forages declining and oil seeds and speciality crop areas expanding.

Table 1: Crops grown in Alberta (adapted from AARD 2014b: 27-28)

Crop Type	Description	Examples
Cereal	Plants grown for their grains	Barley, Canada Prairie Spring wheat, durum wheat, grain corn, hard red spring wheat, malt barley, oats, rye, soft wheat, triticale, and winter wheat
Forage	Plants consumed by livestock	Alfalfa (two & three cut, hay, and silage), barley silage, brome hay, corn silage, grass hay, green feed, milk vetch, millet, native pasture, oats silage, sorghum/sudan grass, tame pasture, timothy hay, and triticale silage
Oil Seeds	Plants grown for the oil contained in their seeds	Canola, flax, and mustard
Speciality	Fruits and vegetables, horticulture, seed production, pulse crops, and nursery crops	Alfalfa seed, canola seed, carrots, catnip, chick peas, dill, dry beans, dry peas, faba beans, fresh sweet corn, fresh peas, grass seed, hemp, lawn turf, lentils, market gardens, mint, nursery, onions, potatoes, pumpkins, safflower, seed potatoes, small fruit, soy beans, sugar beets, and sunflower
Other	Any other irrigated land use	Miscellaneous, summer-fallow, non-crop and unknown

In terms of water management, the crop mix affects the water demand, as various crops have different water requirements over the length of the growing season (Bennett *et al.* 2014). Figure 11 presents average crop evapotranspiration depths at Lethbridge for some of the major crops grown in southern Alberta, based on Bennett *et al.* (2014) data for a 50% chance of exceedance and calculated with the Penman-Monteith evapotranspiration method. Alfafa hay (forage), has the highest water requirement compared to barley (cereal), which has the lowest. The average seasonal rainfall depth of 279 mm at Lethbridge based on AARD (2014b) data for the year 1970 to 2013 is also indicated on the graph. The difference between the seasonal evapotranspiration and seasonal rainfall value is the average net irrigation water requirement for a given crop (Bennett *et al.* 2014).

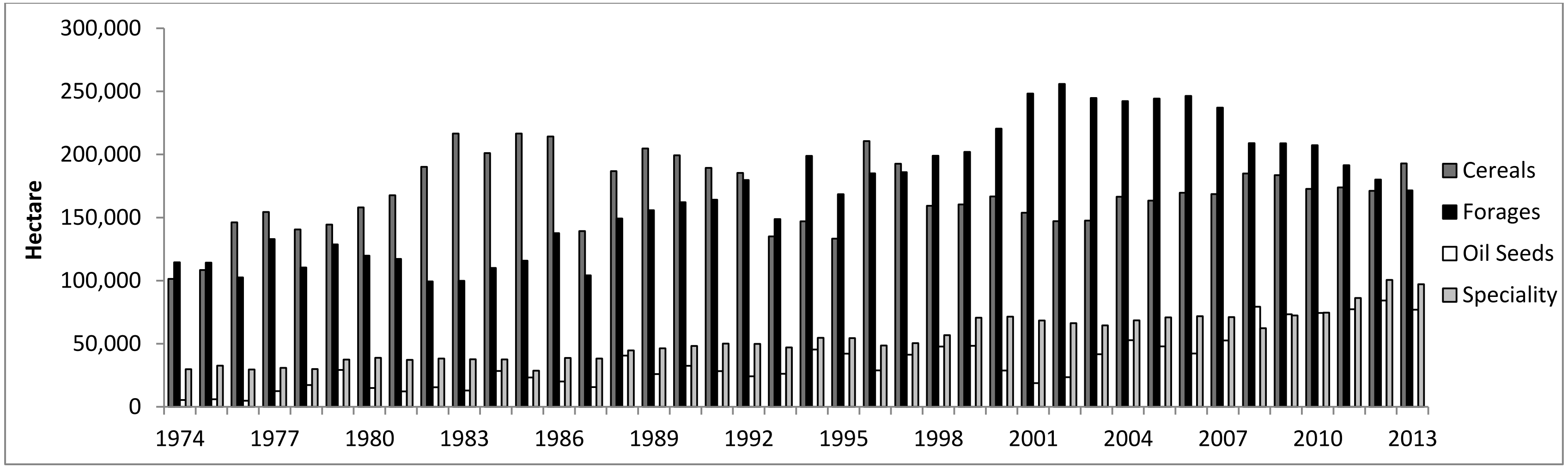


Figure 10: Historical Irrigation Districts' Crops Mix (adapted from AARD data given by Winter 2014)

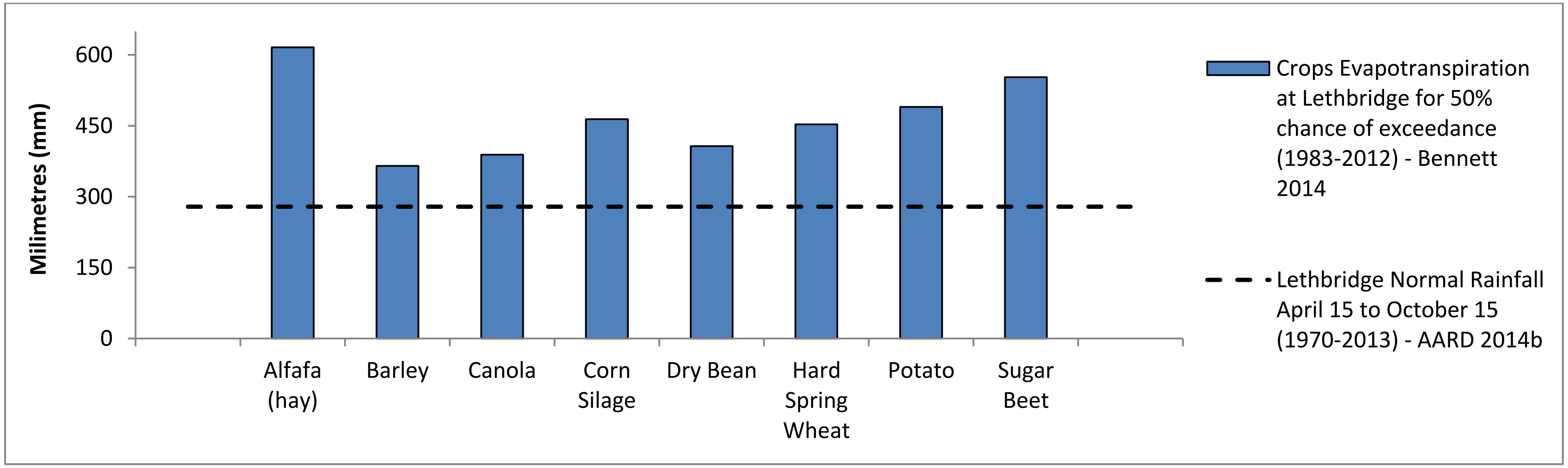


Figure 11: Normal Growing Season Evapotranspiration at 50% Chance of Exceedance and Seasonal Rainfall in Lethbridge (adapted from Bennett *et al.* 2014; AARD 2014b)

2.3.4 Irrigation District Storage Capacity

The thirteen irrigation districts of southern Alberta manage over 50 reservoirs with a total storage capacity of nearly 3 billion cubic meters (AARD 2014). More specifically, Table 2 presents storage and diversion facts for each irrigation district. The licensed water supply, main licence issuing date and average gross diversion volumes for the last five years (2009-2013) give an idea of their relative size and seniority. Their internal water storage capacity, which corresponds only to the reservoirs owned by the districts, their total water storage capacity, which includes both internal and provincially-owned reservoirs, and the ratio of storage capacity to a five-year average gross diversion volume indicate how well an irrigation district is supported by reservoirs. Some districts share provincially-owned reservoirs, such as St. Mary River Irrigation District (SMRID) and the smaller Taber (TID), Raymond (RID) and Magrath Irrigation Districts (MID).

Many irrigation districts can store more than 100% of their average annual water diversion in reservoirs. Indeed, the storage capacity can vary from as low as a few days to as much as a year's supply for the largest reservoirs. However, the ratio of storage capacity over the previous gross diversion volume is not always a good indicator of how well supported an irrigation district is by reservoirs, because provincially-owned reservoirs can serve other purposes than irrigation, including flood mitigation and recreation, and the configuration of each district's canal network means that irrigators may rely entirely on river diversions if they are not downstream of a reservoir. The numerical values presented in Table 2 are calculated from published data of Alberta Agriculture and Rural Development (2014b).

Table 2 : Irrigation District's Facts

Basin	Irrigation District[1]	Total Licenced Volume (dam^3)[2]	Main Licences Seniority (Issuing Date)[3]	5 years AVG Gross Diversion (GD5) (dam^3)	Internal Storage Capacity (ISC) (dam^3)	Total Storage Capacity (TSC) (dam^3)	TSC/GD5 (%)	Expansion Limit (ha)[4]	5 years AVG Irrigated Land (ha)
Bow River Basin	WID	195,307	**1903**090401	117,381	12,840	12,840	11	38,445	20,836
	BRID	554,850	**1908**102702/**1913**032501	272,092	78,810	555,590	204	105,218	82,732
	EID	939,546	**1903**090402	414,991	546,350	546,350	132	125,857	113,782
Oldman River Basin	LNID	412,377	**1917**111601	172,620	3,050	588,870	341	91,864	71,304
	SMRID	890,226	**1899**020701/**1950**053107	373,155	443,520	1,088,360	204	166,731	138,831
	TID	194,814	**1899**020702/**1950**053118	98,950	16,560			37,312	30,625
	RID	99,873	**1899**020703/**1950**053115	43,170	1,480			18,818	14,100
	MID	41,922	**1899**020704/**1950**053110	18,100	0			7,406	5,009
	UID	81,637	**1919**032401	20,093	3,100	3,100	15	13,921	8,667
	LID	14,796	**1939**061701	5,885	0	8,690	73	2,428	1,277
	AID	11,097	**1945**063001	3,378	0			2,023	935
	MVID	9,864	**1923**071003	2,564	0			1,716	457
	RCID	3,699	**1951**030201	919	0	4,630	504	490	291

[1] Acronyms : Western Irrigation District (WID), Bow River ID (BRID), Eastern ID (EID), Lethbridge Northern ID (LNID), St. Mary River ID (SMRID), Taber ID (TID), Raymond ID (RID), Magrath ID (MID), United ID (UID), Leavitt ID (LID), Aetna ID (AID) Mountain View ID (MVID) and Ross Creek ID (RCID)

[2] 1 dam^3 = 1,000 m^3 = 0.8107 acre-feet

[3] Priority is based on the date of application for a licence. The priority number represents the year (bolded), month, day of the application and same-day applications priority. Each licence is valid for a specific water source. In the case of the Oldman River basin districts, there are licences issued for the Oldman, St. Mary, Waterton, Belly or Gros Ventre Creek Rivers. The complete list of the irrigation districts' licences is detailed by IWMSC (2002a).

[4] 1 ha = 10,000 m^2 = 2.47105 acres

3. River Basin Modelling

Water resources management could benefit from computer modelling to develop or improve reservoir operations for the beneficial use of water in the context of social and environmental uncertainty or infrastructure development planning alternatives (Labadie 2004; Wurbs 1993). The often multi-purpose uses of reservoir storage and the stochastic nature of precipitation and reservoir inflows add to the complexity of developing the appropriate modelling tools to achieve efficient management of water resources system (Alcigeimes *et al.* 2009; Fayaed *et al.* 2014). The following sections present the river basin modelling theory and highlight the gaps identified to be filled through further research advances. The section describes the river basin modelling approaches, with a particular focus on the network-flow programming formulation as it is the method used by this research, as well as two optimization techniques that could be applied and the main concepts behind reservoir operating curves. The ongoing challenge of applying theoretical output in real-world operations is described, and previous studies related to water resources management of the SSRB are reported.

3.1 River Basin Modelling Approaches

River basin models are oriented to either assist descriptive or prescriptive studies. Wurbs (1993: 468) defines descriptive models as those simulating "what will happen if a specified plan is adopted" while prescriptive models are determining "the plan that should be adopted to best satisfy the decision criteria". For example, a descriptive model would help quantify the risks of adopting alternative reservoir operating rules for water shortages whereas a prescriptive model could generate the optimal reservoir operating rules to guarantee a pre-defined maximum level of risk for water shortages. River basin models could also be categorized between simulation and optimization models. The simulation models are typically associated with descriptive studies while optimization models with prescriptive ones; however, the distinction is not rigid as most models can incorporate elements of both approaches (Fayaed *et al.* 2014; Wurbs 1993).

3.1.1 Simulation

Simulation models represent the physical characteristics of the river basin system and are used to predict the system response under various set of conditions based on the water mass-balance. In fact, Yeh (1985: 1809) indicated that the use of simulation models "enables a decision maker to examine the consequences of various scenarios of an existing system or a new system without actually building it".

Among all, the simulation models can assess the impact on the water allocations of alternative reservoir configurations, storage capacity and operating rules as well as the effect of changing the demand levels, and inflow sequences (Wurbs 1993).

Simulation models have the advantage of providing detailed performances of the river basin system but have the downside to often require an explicit statement of the operating rules. As a result, the operating policies have to be pre-defined by the modeller rather than prescribed by the model. The operating rules aim to provide unambiguous operational instructions of reservoir release decisions for the simulation model and are typically based on known variables such as current reservoir storage or inflows, and sometimes forecast conditions such as future estimates of inflows and demands (Lund & Guzman 1996). The identification of effective operating guidelines could be a challenging task when addressing complex multi-purpose multi-reservoir systems. On the other hand, simulations models could be used to generate a near optimal solution when multiple runs are compared and refined (Wurbs 1993).

3.1.2 Optimization

As opposed to the descriptive analysis generally provided by simulation models, optimization methods are designed to define the optimal management alternative leading to the highest system performance. Indeed, optimization models evaluate all possible decision options to retain the most ideal one (Yeh 1985). Optimization models use an objective function, decision variables, and constraints to define mathematically the costs and benefits related to the optimal reservoir operations and water supply allocations possible under the physical and legal characteristics of the water network (Ilich 2011; Lund & Guzman 1996; Wurbs 1993). The mathematical programming techniques commonly used to solve the optimality problem are linear programming, dynamic programming, nonlinear programming or other artificial intelligence methods. Furthermore, these techniques can be applied in a deterministic environment, which is described by a pre-defined inflow time-series or in a stochastic environment represented by a probabilistic description of the hydrological conditions; referred respectively as Implicit Stochastic Optimization (ISO) and Explicit Stochastic Optimization (ESO) (Labadie, 2004; Loucks & van Beek 2005; Fayaed *et al.* 2014; Wurbs 1993).

Optimization models have been applied to real-time operations of reservoir by optimizing water allocations over hourly or daily time-steps. They often require the use of flow routing components and real-time forecasting of inflows and demands. More recently, decision support systems have been developed to incorporate reservoir operators' control over optimization tools applied to reservoir operations. This kind of systems has improved the applicability of optimization theory in real-world operations as they empower water manager judgement (Labadie 2004).

On the other hand, because optimization models involve complex numerical solution algorithms to prescribe optimal operating decisions, their solvability also requires important simplifications of the river basin system, which reduces their accuracy (Lund & Guzman 1996). Moreover, not all optimization techniques are guaranteed to find the optimum solution, as some model output could only correspond to a local optimum solution (Loucks and van Beek 2005).

3.1.3 Simulation-Optimization

Finally, some models can incorporate both simulation and optimization features in order to address the weaknesses of one approach with the strengths of the other (Kang and Park 2014). For example, optimization can be used to develop a first screening of various management alternatives before a more detailed analysis is executed with simulation modelling (Fayaed *et al.* 2013; Wurbs 1993). Alternatively, an optimization model might include automated iterative executions of a simulation model in order to take into account the river basin system complexity without having to formally include it in the optimization algorithm (Wurbs 1993).

Finally, the network-flow programming models are a particular type of combined simulation and optimization techniques, which can be used for research work on operations and planning of river basin system. The Water Resources Management Model (WRMM) used for this research project is based on a network-flow programming formulation; thus, this type of model is further detailed.

3.2 Network-flow Programming Models

Numerous river-basin models are based on the network-flow programming approach and have seen application worldwide. Network-flow programming models are usually formulated as a "minimum-cost capacitated network-flow problem" (Wurbs 1993: 463), because the river network is modelled by associating cost factors (or penalty points) with the amount of water flowing in each interconnected river system components, each having specific flow capacities. Through the use of the predefined penalty point scheme, these models can represent the seniority-based water licence system of Alberta.

Indeed, network-flow programming models derive an optimal allocation of water subject to the priority of use of each licensee (Ilich 2011).

The river basin system components are represented through the interconnection of arcs and nodes. The arcs represent the flows that can be convey through the river reaches, diversion canals, reservoir releases or the evaporative and other losses of the system while the nodes can represent canal junctions, reservoir storages and water user demands. A series of constraints are defined to maintain the mass-balance and the physical limits of the system. The relative priority of use of each component – such as water licences, reservoir storage levels, or the minimum flow rate to maintain in a canal – is represented through the penalty scheme, which identifies for each pair of arc a unit-cost factor (Ilich 2009; Labadie 2004; Wurbs 1993).

Equation (1) defines the objective function of the minimum-cost flow problem, equation (2) corresponds to the mass balance constraint, and equation (3) represents mathematically the physical, environmental or legal constraints governing the minimum and maximum flow limits to maintain in each arc of the system network

$$Minimize \sum_{(i,j)\in A} c_{ij}x_{ij} \quad \forall\, i,j\ \in N \tag{1}$$

$$Subject\ to\colon \sum_{i} x_{ij} - \sum_{i} x_{ji} = 0\ \ \forall\, i \in N \tag{2}$$

$$0 \le l_{ji} \le x_{ij} \le u_{ji}\ \ \forall\,(i,j) \in A \tag{3}$$

where A is the total of ordered pairs (i, j) of arcs representing the river basin network and N is the total of nodes i and j; with the water flowing from node i to node j. The variable c_{ij} is the cost factor per unit of flow along each arc, while x_{ij} is called the decision variable and it represents the flow in a given arc (i, j). Finally, l_{ij} and u_{ij} are respectively the lower and the upper bound of the possible flow along each arc (i, j) (Ilich 2009; Wurbs 1993).

By convention, the objective function of the model is presented as detailed by equation (1), which aims to minimize the total cost of the system by multiplying the flow of each arc with its associated cost at each time-step. However, the objective function programmed in river-basin models needs to be converted into a maximization problem as the optimization algorithm should identify the optimal water resources allocation that will maximize the supply available to all components of the system according to their priority of uses. The algorithm can be converted to a maximization problem by adding a negative sign in the objective function or by minimizing the cost associated with the water deficit of each arc rather than the supplied flows (Ilich 2009).

The network-flow problem is solved by linear programming techniques such as the Out-of-Kilter algorithm (Fulkerson 1961) or the more recent improved algorithm referred to as the SUPERK algorithm (Barr *et al.* 1974), which is currently used in the WRMM. A detailed description of the theoretical fundaments of the Out-of-Kilter and its improved version used by the WRMM are described in the Appendix A of the WRMM Computer Program Description (Alberta Environment 2002).

Usually, the network-flow models handle non-network constraints by an iterative process external to the algorithm that is repeated at each time-step until the results converge to optimality. Non-network constraints refer to flows interdependence from one component to another such as routing flow patterns, evaporative losses, or return flows. However, in two different papers, Ilich (2008; 2009) reported the inability of network-flow algorithm to properly converge to optimality when simulating reservoirs with multiple outflows whose flow rate varies according to the reservoir level. The effect of this particular non-network constraint was even tested under various time-step length and penalty schemes without success. The network-flow model limitations are attributed to the solver process, which does not include directly the flow relationships (Ilich 2009).

Haro *et al.* (2012) also noted convergence problems when applying three different network-flow algorithms – Out-of-Kilter, RELAX-IV and NETFLO – to the Duero River basin system in Spain. They found that under the iterative process to solve non-network constraints, the Out-of-Kilter algorithm was the only one that converged to a solution in a small number of iterations. Chou and Wu (2014) partially addressed the convergence problem by applying a linear programming algorithm in a network-flow model, which permits incorporation of the non-network constraints directly in the solution procedure. Their study also detailed a method to generate the appropriate cost factors in the objective function that would preserve the river-system constraints and operating policies. Their methodology was applied to determine water allocations for the Feitsui and Shihmen joint reservoir system of northern Taiwan, but they indicated the need to derive a comprehensive approach, which could encompass all types of river system constraints represented in network-flow models and solved by linear programming algorithms.

Over the years, a number of network-flow models have updated their optimization solvers with linear programming methods that can include the non-network constraints directly in the model algorithm. More particularly, AEP (formerly AESRD) is currently in the process of updating the WRMM optimization solver in order to improve model accuracy and capabilities under the future Water Resource Management-Decision Support System (WRM-DSS). This model had been using an external optimization model, the Linear, Interactive and Discrete Optimizer (LINDO) solver, created by Lindo Systems Inc. and more recently, the WRM-DSS has been run with an open-source mixed-integer program, the COIN Branch and Cut (CBC) solver instead of the improved Out-of-Kilter algorithm from Barr *et al.* (1974). The future WRMM version should eventually present considerable advantages over the current version of WRMM, as it will give more realistic results under non-linear constraints on flows, which are recurrent in a large and complex watershed such as the SSRB; however, it is still under development and it is not yet available for external users and public (Reza Ghanbarpour, personal communication, AESRD, July 2015). Existing network-flow programming models able to simulate non-network constraints include the California Water Resources Simulation Model (CALSIM) (Draper *et al.* 2004), the Options Analysis in Irrigation Systems (OASIS) (Hydrologics Inc. 2009) and the Water Evaluation and Planning (WEAP) model (Stockholm Environment Institute 2011).

3.3 Optimization Techniques

Water management models could solve the optimal water allocations for each individual time interval separately or over all the time intervals encompassing the full simulation cycle length (Ilich 2011; Wurbs 1993). Ilich (2011) defined respectively the two types of computations as Single Time-step Optimization (STO) and Multiple Time-step Optimization (MTO). The various specifications of the two optimization techniques are described in the following section.

3.3.1 Single Time-step Optimization

In Single Time-step Optimization (STO) applied to water resources allocation problems, the minimization or maximization of the objective function under the defined constraints is performed at each time-step without any consideration of the previous or future released decision, runoff inflows or water demands. In other words, STO simulations are able to spatially optimize the allocation of water over a single time-step window. The STO approach has the advantage of being simpler to solve and to code in water resources models than the MTO technique. Furthermore, because this method takes into account only the current state of the system, it is also recognized to represent the foresight limitations experienced by the reservoir operators (Ilich 2011).

However, because STO models optimize on a time-step basis, severe water deficits are more likely to occur as depicted by Figure 12 (Ilich 2011). Indeed, the figure illustrates a hypothetical ideal irrigation demand and the achieved supply possibly simulated by an STO model. The demand is fully met until July by releasing water from a reservoir upstream. When the reservoir becomes empty and no more water is available to meet the ideal demand, the achieved supply drops to zero until the reservoir can supply the demand again in September. This allocation solution is certainly sub-optimal for two reasons. First of all, the crop yield response to water shortages is not a linear function, but is rather influenced by the severity and timing of the water deficits as well as the growing stage of the crop grown (Zhang 2003). In the example illustrated by Figure 12, the crops is likely to experience severe yield reduction as the deficit in water occurs in the warmest period of the growing season (August) and during the last stages of development. Moreover, considering the highly damaged condition of the crops after a month of water shortage, the water releases effectuated in September are probably not providing tangible yield benefits; thus, the water could had been instead kept in the reservoir as carry-over for the next irrigation season.

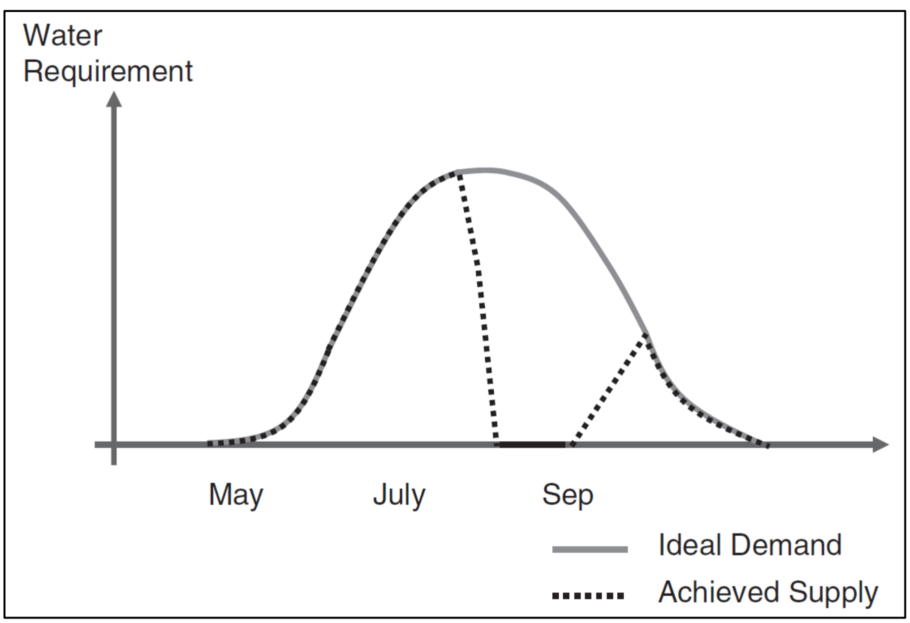


Figure 12: Ideal Water Demand and Possible STO Achieved Water Supply (Ilich 2011)

To impede the kind of situation that was illustrated by Figure 12, the definition of reservoir rule curves or other type of water management policies can be implemented in the STO model. Explicit operating statements provide release guidelines to the model reservoir, which would optimize the water allocations to satisfy best the operating policies as well as the ideal demand. However, defining the appropriate operating rules that would lead to satisfactory simulation results in complex river system could be a challenging task. More importantly, because the operating guidelines are user-specified, there is no guarantee that the model will reach optimality under STO simulations, which is the main limitation of this optimization technique. However, STO simulations can provide useful input on the limitations and benefits of alternative operating policies (Ilich 2011).

Alternatively, STO can be performed in an explicitly stochastic environment, identified earlier as Explicit Stochastic Optimization (ESO), in which the streamflow processes and other variables are defined by probabilistic equations and are taken into consideration in the solution procedure. At each time-step, the model evaluates the optimal water allocations given the current state of the system and the expected benefits of future decisions, which depend on both the current decisions and future random inflow sequences. It allows the model to find the optimal water allocation at each time-step while taking the uncertainties of future variables into account, similar to reservoir operators' decision processes in real-world operations. However, ESO applications necessitate a large number of possible scenarios results to be analysed simultaneously, which greatly increases the computational requirements of the model (Labadie 2004).

3.3.2 Multiple Time-step Optimization

Multiple Time-step Optimization (MTO) has the potential to allocate water best within a river basin network because it considers the water supply and demand not only spatially such as does STO models, but also temporally. This type of optimization method minimizes the overall cost of water deficits in the river system over the length of the simulation by a perfect foreknowledge of future inflows and demands. Therefore, as opposed to the STO approach, MTO models do not require user-defined reservoir operating rules. Indeed, for all the years being simulated, MTO models generate unique optimal reservoir storage curves given the initial condition of the system, the inflow time-series, the various demand levels and the allocation priorities. The MTO models generally solve the optimal water allocation problem in a deterministic environment in which the hydrologic sequence is determined by historical data or is generated synthetically under pre-defined hydrological parameters (Ilich 2011).

Because the inflow time-series is fixed for the simulation, this kind of computation is generally referred as Implicit Stochastic Optimization (ISO) or Monte Carlo optimization (Labadie 2004).

In order to optimize the water allocations over one simulation cycle, the objective function should maximize the system-wide water benefits over all time-steps simultaneously, as shown in equation (4):

$$Maximize \sum_{t} \sum_{i \in A} C_i Y_{i,t} \tag{4}$$

where t represents all the time-steps over which the solution is optimized, i is an individual component of the system from the ensemble A, $Y_{i,t}$ is the decision variable corresponding to the allocated flow to each component at each time-step and C_i is the cost or the priority of allocation associated with each component.

Ilich (2011) proposed an additional constraint for an MTO model that further equalizes the water deficits over the simulation cycle in order to distribute the total deficit uniformly over the season,

$$Distributed\ Deficit\colon\ \frac{Y_{i,t}}{D_{i,t}} = \frac{Y_{i,t+1}}{D_{i,t+1}}\ \ \forall\ t = 1,..,n-1\ \ and\ \ i\ \in A \tag{5}$$

where $D_{i,t}$ is the ideal irrigation demand at each time-step and for each component of the system and $Y_{i,t}$ is the allocated supply to the same irrigation user. However, Huggard (2014) suggests that hedging the water supply using the constraint in equation (5) affects the optimality of the MTO results. Indeed, the simulated water allocation is conditioned by the lowest of the achievable supply at one particular time-step, which restricts the overall available supply. Therefore, further work is necessary to develop an MTO algorithm that will generate truly optimal water allocation results.

Furthermore, the "perfect" solution potentially achievable by the MTO approach poses a problem in terms of results applicability to real-world operations. Indeed, MTO model algorithms require foresight of the demand and supply over typically a full-year period whereas reservoir operators can only take into account the current state of the system and, sometimes, limited forecast information in their decisions. To bridge the gap between MTO theory and practicability, the resulting large set of optimal operating solutions produced by MTO models could be examined in order to develop seasonal operating guidelines conditioned by information normally available to operators. For example, multiple regression analysis, standard statistical tools or more advanced interpolation methods such as neural network technique can find matching pattern with optimal reservoir level and other variables such as the current reservoir level, previous inflows or forecasted inflows. As a result, MTO models could be used to derive dynamic operating rules that could be further tested in simulations performed in a probabilistic environment under ESO and eventually, be applicable in daily reservoir operations (Alcigeimes *et al.* 2009; Cancelliere *et al.* 2002; Ilich 2011; Karamouz & Houck 1982; Labadie 2004). Labadie (2004) however advises that defining the operating rules from MTO simulations could be a cumbersome task leading to unsatisfactory results.

Nevertheless, the literature offers promising examples of inferred seasonal operating rules by MTO output analysis performed in a deterministic environment. This approach was first proposed by Young (1967) and various studies have followed. Among the most recent cases, Cancellieres *et al.* (2002) used a two stage dynamic programming optimization technique with a neural network-based method to determine optimal operating rules for an irrigation supply reservoir. The model was applied to the Pozzillo reservoir on Salso River in Sicily under a 29-year time-series of historical inflows, and performance results obtained from the two optimization techniques were compared for an additional 7-year timespan of historical inflows. Alcigeimes *et al.* (2009) applied the ISO approach in conjunction with a regression analysis and a two-dimensional interpolation strategy to develop operating rules, which further incorporated inflow uncertainties for the reservoir operations in a semiarid region of Brazil. The model performance under the derived operating rules applied in a stochastic environment was similar to the optimal results produced under the deterministic approach. Dariane & Karami (2014) used an optimization method to derive a long-term set of optimum reservoir releases, which were then submitted to the combined analysis of an artificial neural network and heuristic approaches to develop optimum operating policies for Tehran water resources system. Kang & Park (2014) applied a simulation-optimization model, which derived optimal operations of both the Balan Reservoir and Seomjingang Dam in South Korea and was further used to establish new operation rules that could be applied to real-time reservoir operations. Ilich (2011) derived operating zones for the Oldman Dam Reservoir from MTO output corresponding to dry to wet conditions in order to provide operating guidelines varying according to the water supply expected by snowpack surveys. The operating rules developed using MTO data could then be transferred to an STO model to evaluate their applicability in real-world operations. Figure 13 from Ilich (2011) illustrates how the simulated reservoir level obtained with STO becomes closer to the MTO solution when the operating curve of the reservoir is modified from the analysis of MTO results compare with the STO solution produced without any reservoir operating guidelines.

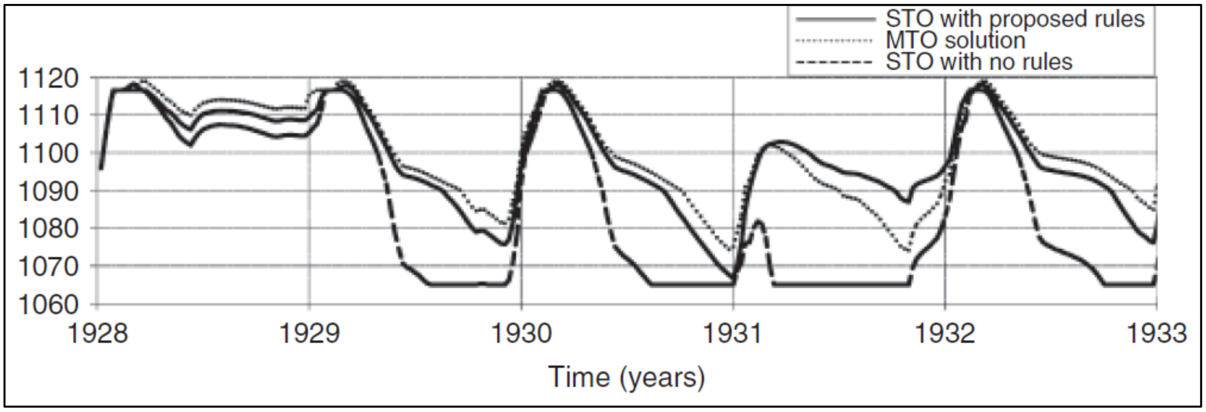


Figure 13: Comparison of Reservoir Levels Simulated by MTO, STO and STO combined with MTO based Operating Guidelines Models (Ilich 2011)

The WRMM version used for this study derives an optimal allocation of water under the network-flow programming algorithm at each time-step individually, and thus operates in a STO mode. The more recent version currently under development, the Distributed Deficit WRMM, will solve the water allocation problem under MTO in addition to STO.

As the STO method usually requires the definition of reservoir rule curves, which are not based yet on the MTO results interpretation, the following section provides an overview of the existing reservoir operating rule concepts.

3.4 Reservoir Rule Curves

Reservoir rule-curves guide reservoir releases to meet water supply and other water-use objectives (Draper & Lund 2004; Labadie 2004; Lund 1996; Wurbs 1996). General rules of thumb for reservoir operation are sometimes applied in real-world operations but cannot ensure optimal water management on a basin-scale basis or for complex multi-purpose multi-reservoir systems (Oliveira & Loucks 1997). Therefore, rule curves are usually defined from simulation models but can also be developed by the analysis of optimization model outputs (Ilich 2011; Labadie 2004; Wurbs 1996).

The U.S. Army Corps of Engineers provided an extensive review of typical operating rules for two configuration types of reservoirs: in series and in parallel (Beard *et al.* 1977; Lund 1996), which was further refined by Lund & Guzman (1999) for the type of reservoir purposes as summarized in Table 3.

Table 3: Conceptual Rules for Reservoirs in Series and in Parallel adapted from Lund & Guzman (1999)

	Reservoirs in Series		**Reservoirs in Parallel**	
Reservoir Purpose/Season	Refill Season	Drawdown Season	Refill Season	Drawdown Season
Water Supply	Fill upper reservoirs first	Empty lower reservoirs first	Equalize probability of seasonal spill among reservoirs	Equalize probability of emptying among reservoirs
Flood Control	Fill upper reservoirs first	Empty lower reservoirs first	Leave more storage space in reservoirs subject to flooding	N. A.
Energy Storage	Fill upper reservoirs first	Empty lower reservoirs first	Equalize expected value of refill season energy spill among reservoirs	Equalize expected value of refill season energy spill among reservoirs for the last time-step
Hydropower Production	Maximize storage in reservoirs with greatest energy production			
Recreation	Equalize marginal recreation improvement of additional storage among reservoirs			

In terms of individual reservoir operating rules, Beard *et al.* (1977) described a zone-based policy, which specifies seasonal storage elevation targets for each purpose of the reservoir. The zone-based policy can also be used to manage a single-purpose reservoir, particularly one for water supply providing that each zone specifies release-reduction targets to allow various levels of water conservation when the water supply decreases. Figure 14 illustrates a zone-based policy curves in which the flood control zone provides room for flood runoff while the conservation zone is the ideal level to maintain in the reservoir for ensuring water supply without affecting flood mitigation measures and finally, the buffer zone is the minimum storage to maintain for water supply under water conservation measures.

Similarly to the zone-based policy described above, the reservoir operations in the WRMM are guided by an ideal storage curve as well as zones above and below the ideal curve, which are specific to each reservoir simulated. The reservoir operations simulated in the WRMM are further detailed in Section 5.1, below.

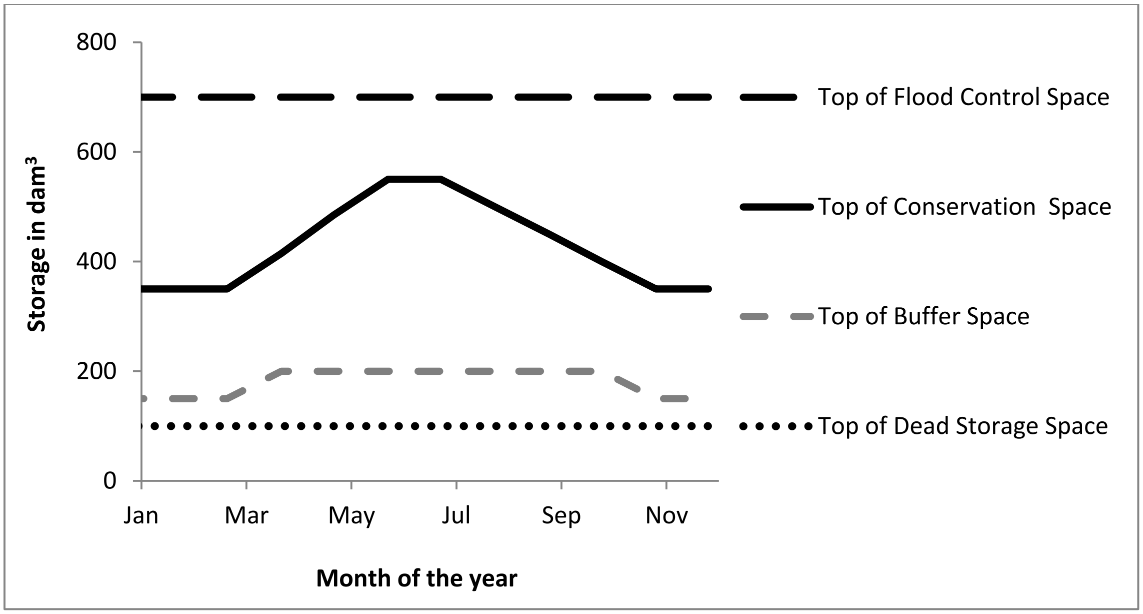


Figure 14: Zone-Based Policy adapted from Beard *et al.* (1977)

The literature also describes other theoretical rule-curves for reservoir releases, which are a function of the available water supply and water demand such as the standard operating policy or the hedging rules policy (Draper & Lund 2004; Lund 1996). Figure 15 presents the standard operating policy and a simple hedging rule policy. The standard operating policy is appropriate when meeting the immediate downstream demand has the highest priority. However, when future inflows are likely insufficient to meet downstream demand and the losses generated by the water deficits are non-linear – i.e. when "the severity of shortages is more important than their frequency" (Lund, 1996) – the hedging rule policy becomes more appropriate. Similarly to the zone-based policy applied for a single-purpose reservoir, the hedging rule policy aims to minimize impacts of future water shortages by the carry-over storage, which results in not supplying the totality of the demand in the short term while permitting future releases (Beard *et al*. 1977). Multiple variations of the hedging rule curves have been developed based on the form of the deficit's loss function and various optimization methods (Hashimoto *et al.* 1982).

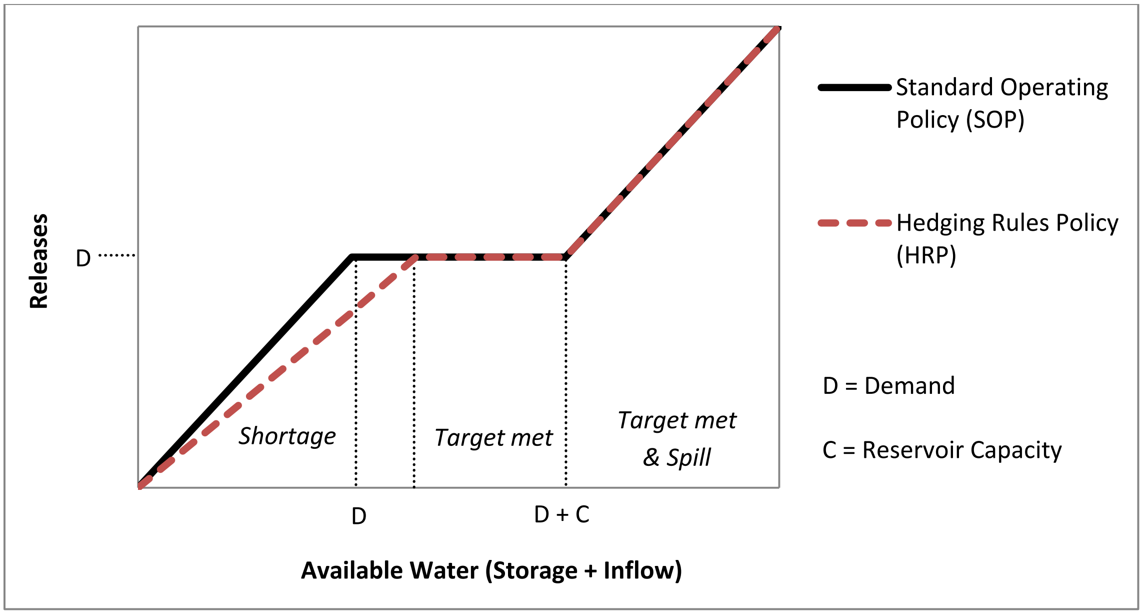


Figure 15: Standard Operating Policy and Hedging Rule Policy adapted from Lund (1996)

There is a recognized value in establishing optimal hedging rule policies, because reservoir systems have to cope with an increasing water demand and uncertain water supply (You & Cai 2006). Draper & Lund (2004) indicated how a hedging rule policy can be derived by means of the release benefit and carry-over storage value functions. Shiau & Lee (2005) derived optimal hedging rules based on compromising short- and long-term water deficits for the Shihmen reservoir in Taiwan. You & Cai (2008) lead a theoretical analysis on reservoir operations with hedging rules that included explicitly the uncertainty of future reservoir inflows. Moghadsi *et al.* (2013) developed a reservoir hedging rule for the Zayandeh-Rud reservoir in Iran that reduces releases from the reservoir according to the inflow and irrigation demand variation. Bolouri-Yazdeli *et al.* (2014) compared various operating rules for the Karoon IV reservoir in Iran, located on the Karoon River. Figure 16 presents how reservoir releases could vary according to the operating rules simulated by the model. In the case of the standard operating policy, the full water demand is met until the reservoir is empty, which results in an important and abrupt water shortage. Under the Stochastic Dynamic Programming (SDP) rule, the model could meet part of the demand for a longer time by optimizing the reservoir release decisions using probability distributions of future inflows within a discretized number of alternatives. Finally, the optimal results are obtained under the Q2S3-Rule, a nonlinear decision rule, which solves the optimal reservoir release solution by evaluating all possibilities in a continuous manner and under nonlinear constraints representation.

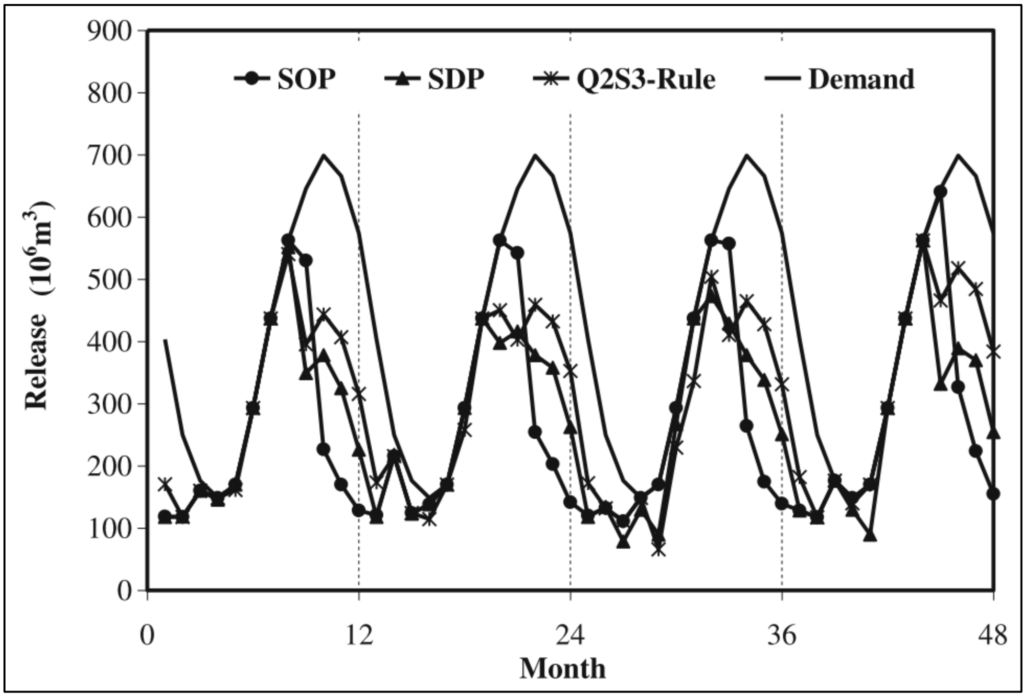


Figure 16: Reservoir Releases based on Three Operational Rules (Bolouri *et al.* 2014)

Additional operating rules that have seen more limited application in the literature include the pack rules that indicate how to manage the available water in excess of targets; the storage target rules that are used for short-term operations by conditioning the water released on both the expected inflows and the difference between the current storage and target level; the New York City rule and its derived versions that are based on the equalization of probability of spill for each reservoir in parallel within the same system; and finally, other complex releases rules that intend to meet multiple objectives that vary according to the month of the year, the reservoir location in the system, the current state of the system and the forecasted information (Lund 1996; Lund & Guzman 1999).

3.5 Connecting Theory and Practice

Despite progress in reservoir modelling and management with the improvement of computer capabilities and the development of numerous optimization methods, managers and decision-makers still face the challenge of applying the output of more-theoretical optimization models to real-world reservoir operations (Labadie 2004; Simonovic 1992; Yeh 1985; Wurbs 1993). The possible reasons for the ongoing gap between the theory and practice in using optimization models' output could include operators' skepticism about the prescribed solutions, unwillingness to accept the necessary simplifications of the river basin system, the mathematical complexity of optimization algorithms, their often inability to incorporate risk and uncertainty, the confusion created by the range of solution methods available and their various applications, and in certain cases the model's deterministic approach, which produces only solutions validated over period-of-record data (Labadie 2004; Loucks and van Beek 2005). Similarly for simulation models, Black *et al.* (2014) reported that result implementation has been compromised by stakeholder doubt of a model's credibility, the difficulty of understanding its outputs and the inconsistencies of approaches and applications.

Stakeholder participation in the water resources modelling process is viewed as a response to address this issue (Black *et al.* 2014; Labadie 2004). Indeed, even several decades ago, Simonovic (1992) indicated that a further integration of knowledge-based technology with existing simulation and optimization tools could permit improvement of education in, and knowledge-transfer of, modelling work from theory to practice. Still today, however, the water resources literature is poor in examples of stakeholder involvement in model development.

Toebes & Rukvichai (1978) interviewed reservoir managers for their work on the daily operations of the Green River Basin multipurpose reservoirs system located in Kentucky, USA. They documented informal procedures developed by the operators in order to minimize the deviations between their optimization model and historical reservoir releases. Unfortunately, they did not report their interview data but rather concentrated their report on the optimization model features. A more recent study attempted to understand operators' decisions by analysing the relationships of historical releases of 79 reservoirs in California and the Great Plains to factors such as current inflow, previous releases and previous storage using mutual information, a nonlinear approach (Hejazi *et al.* 2008). This study provided a good overview of the factors affecting operators' decision making, but used indirect data to describe water managers' behaviour. Kodijara *et al.* (2010) conducted an interview-assisted questionnaire survey to derive the preference functions and weights of performance measures later used to evaluate the alternative operating rules of the Melbourne urban water supply reservoir system in Australia. They interviewed water managers as well as water users and environmental interest groups. Sheer *et al.* (2013) determined new operating procedures for the Bow River basin in Alberta through Collaborative Modelling for Decision Support, which involved stakeholder participation from the agriculture, municipal and environmental interest groups. The approach permitted inclusion of stakeholders' perspectives in the modelling steps to define robust performance measures and provided the additional benefit of enhancing stakeholders understanding of each other's interests. Similarly as the previous case, the involvement of the stakeholders was particularly useful to determine the “best” solution but not necessary to facilitate knowledge transfer between the water operator and model formulation.

In order to improve understanding of the behaviour of reservoir operators under different climatic and hydrological conditions such as the data they rely on and their decision-making processes, further research work is needed. As a result, the fundamental behaviour of optimization models could be reviewed by incorporating more information from water managers, which could enhance their acceptability and applicability in real-world operations.

3.6 Water Resource Modelling of the SSRB

Water resources modelling studies have been conducted to assess the effects of changing supply and demand in the SSRB and to improve water management to meet environmental, economic and social needs. In terms of water management investigations, Ali & Klein (2013) compared the economic effect of the current water allocation policy based on the seniority rule with three alternatives allocation policies; “people-first”, proportional sharing of shortages among all users and a trading policy favouring costless trades during droughts. Their study involved water demands from irrigation and non-irrigation users of the Bow River Basin. They conclude that a proportional sharing of the water deficits is overall more beneficial as it produced the highest net returns. AMEC (2014) identified new storage opportunities within the SSRB to improve the reliability of junior licence holders and the protection of the aquatic environment during water shortage years.

Other studies analyzed the consequences of changing water demand. Several years ago, the IWMSC (2002a) evaluated the impact of various scenarios of irrigation expansion, shifts in crop mixes and efficiency improvements of on-farm systems. AECOM (2009) was mandated by a multi-stakeholder steering committee to assess best avenues for improving the conservation, efficiency and productivity of the irrigation sector in Alberta. Wang *et al.* (2014) recently surveyed irrigators in southern Alberta to analyse the adoption of irrigation scheduling methods. Based on an econometric approach they reported the intensity of adoptions observable and the main factors influencing irrigators practice.

Finally, there are a number of studies integrating the water demand, water supply and, sometimes, the water management aspect. For example, AMEC (2009a) estimated the risks for the SRRB of future water supply and demand anticipated under climate change and economic development as of 2030. Alberta Environment (2010) evaluated the impact on water deficits of nine consecutive drought years by modifying the historical sequence on current, low and high scenarios of irrigation demand. As a continuation of the work done by Sheer *et al.* (2013), Hill *et al.* (2013) further developed water management strategies based on stakeholder preferences in order to improve the Bow River basin resiliency in facing more severe climate conditions. Islam and Gan (2014) applied a hydrological model (MISBA) to estimate the future hydrological and meteorological conditions of the SSRB until the end of the 21st century under four general circulation models of the Intergovernmental Panel on Climate Change. They projected the climate change scenario data in the WRMM to quantify the resulting water deficits for irrigation. Hassanzadeh *et al.* (2014) applied a system dynamics approach to model the Saskatchewan portion of the SSRB. More particularly, their model integrated a dynamic irrigation demand component and economic sub-model. While the model could be used to assess water availability under various states of the system, the water allocation policies and the operational guidelines of the reservoir are not included dynamically in the model and require being user-defined similarly as what was the case for conventional STO models.

3.7 Summary of the Literature Review Gaps Identified

From the previous literature review, the following gaps were identified:

1. Some studies aided understanding of irrigators' practices, but almost none addressed reservoir operators' behaviours directly;
2. It is true that stakeholders' involvement has increased, particularly in evaluating model behaviour, but almost no studies involved water managers' experience in the development of river basin system models;
3. Modelling studies applied to the SSRB generally address "what if" questions more than improving the existing reservoir operation through optimization models;
4. Previous work assessed the impact on the irrigation sector of future water demand and supply scenarios, but no studies has been conducted to evaluate bounding scenarios in terms of water demand, which could help establish the viable limits of river basin systems;
5. The majority of the studies investigating water management alternatives were applied on period-of-record hydrological sequence rather than analysing the combined effects of changing reservoir operations and changing water supply and demand.

To fill these gaps in the literature, further research should focus on improving the understanding of reservoir operators' practices under different climatic and hydrological conditions such as the data they rely on and their decision-making processes; developing and applying MTO models in order to assess water allocation optimality; establishing bounding limits of the water supply available to meet future irrigation demand; and evaluating the robustness of new water management alternatives under changing water supply and demand scenarios to cope better with future water availability challenges.

This thesis aims to address some of the identified research needs by interviewing water managers of the SSRB. It is believed that the real-world data collected could contribute to a better understanding of water managers' perspectives that may lead to more valuable outcomes from modelling studies, and results that may be more readily adopted by water managers. The second focus of this study project is the evaluation of the benefits of alternative reservoir management strategies for the Bow River Basin by addressing various reservoir management options in the BRID. Unfortunately, due to the WRMM's current limitations, it was not possible to conduct this analysis with an MTO model. As a result, the simpler STO simulation was performed and different user-defined rule-curves were assessed. Nevertheless, it is expected that future research work could build on the investigation's results. Finally, the thesis permits the establishment of water supply limits for the Bow River Basin under the minimum and maximum irrigation demand levels anticipated for the next 25 years (2040) for dry to wet conditions.

4. Water Managers’ Perspectives on Reservoir Operations for Sustainable Irrigation in Alberta

4.1 Methodology of the Interviews with Water Managers

The first part of the research aims to improve understanding of the decision-making criteria of reservoir operators under different meteorological and hydrological conditions; this greater understanding should improve the applicability of reservoir management models, by allowing an assessment of how closely current reservoir management strategies applied by the reservoir operators match the results from optimization models. In other words, the interviews attempt to compare the reservoir management theory with management practice, and to use a greater understanding of practice from in-person interviews to improve the optimization models used for reservoir management.

To address this goal the project investigated water managers' practices through a qualitative interview methodology. Qualitative research methods have been extensively applied in the social, behavioral and health sciences field over the past twentieth century (Brinkmann 2013); however, this type of methodology has found fewer applications in the engineering and science domain. In fact, as presented in the literature review section, only a few water resources management studies have assessed current reservoir operations and even fewer have involved direct interviews with water managers. It is believed that future river-basin modelling work could be improved by a better understanding of current reservoir operations and, therefore, modellers from other regions of the world are encouraged to apply the following methodology in other geographical and political contexts.

4.1.1 Design Phase 1: Identification of potential interviewees

The first phase of the interview work addressed interviewee selection, which was based on an information-oriented approach. As the study concentrates on southern Alberta, the aim was to select interviewees who represent the people with the greatest experience in, and authority over, reservoir release-decisions and water management strategies applied in the region, and should be as numerous as necessary to cover all the main irrigation reservoir operations in the South Saskatchewan River Basin. The irrigation districts’ water managers were expected to be important participants because they have normally accumulated several decades of water management experience and are likely to be well aware of the different factors affecting their reservoir management strategies. Eight irrigation districts out of the thirteen totals were contacted based on their relative significance in terms of water licences and reservoir storage volume; together, the eight districts possess 97% of the total district water licences and manage about 99% of their collective reservoir storage volume. The smaller irrigation districts, which rely on reservoir storage smaller than 10,000 cubic decameters (10 million cubic meters) were not interviewed (see Table 2).

The irrigation districts contacted all responded positively and include the WID, BRID and EID from the Bow River basin and the LNID, SMRID, TID, RID and MID from the Oldman River basin. The remaining districts (the UID, LID, AID, MVID and RCID) were not interviewed. In addition, employees from the Bow and Oldman Basin Operations of the AEP and from the Basin Water Management Branch of the AAF were also selected as they are involved directly with the management of the provincially own reservoirs and the irrigation in Alberta and would provide additional information from the government point of view. They were identified from the Government of Alberta contact page available online (Government of Alberta 2015).

4.1.2 Design Phase 2: Selection of interview methodology

The second phase consisted of deciding how to collect the interview data. The form of interview adopted for this research is the most widely used in the qualitative research world: the semi-structured interview. Its questions are comparatively short and formulated to encourage interviewees to provide long, detailed and elaborated answers. The interviewee has the attention of the interviewer, who listens to the interviewee's answers without any form of argumentation or judgement. The aim is to obtain a description from experience-based knowledge rather than constructed theorizations and rationalization of facts (Brinkmaan 2013). The individual interviewing approach permits the establishment of an atmosphere of trust where discussion is facilitated.

Face-to-face and phone-call interviews were conducted over the course of the months of August to October 2014.

4.1.3 Design Phase 3: Question design

The interview questions focused on several topics to cover best the different aspects of reservoir operations, from the sources of information used in decision-making to the actual operating guidelines applied for managing individual reservoirs. Different themes were therefore identified, and with them a list of questions associated with each theme. This form of questionnaire served as a guideline for the interviewer in order to ensure that all relevant aspects of the research are covered through the interview process. It is important to emphasize here that all questions are not necessarily asked during the interview and neither are they addressed in a pre-defined order. Indeed, as explained by Rubin & Rubin (2005: 4): “Unlike survey research, in which exactly the same questions are asked to each individual, in qualitative interviews each conversation is unique, as researchers match their questions to what each interviewee knows and is willing to share”. In seven categories, the questions related to,

1) Water network specifications;
2) General water management strategy at district and river basin scales;
3) Water management strategies for reservoirs with different purposes – if applicable;
4) Water management strategies under dry to wet hydrological conditions;
5) Water management tools used and level of familiarity with existing river basin management models;
6) Future irrigation demand trends expected in terms of land, water-uses and crop mixes;
7) Final open remarks and questions.

The motivation behind each theme is further described. The first category of questions was developed to improve understanding of each district’s particular reservoir configuration and water distribution constraints. These questions were also useful to “break the ice” by discussing a comfortable topic for the water manager. Some questions were more specific to the BRID’s network as it was necessary to report information on its current reservoir operational constraints and water delivery infrastructure capacity before conducting the simulation work that address the second and third objectives of this thesis. Moreover, other questions were intended to analyze how well the model assumptions described in the report on the WRMM structure produced by AEP – formerly Alberta Environment (see Alberta Environment 2002) – corresponded to current operations.

The second category of questions aimed to cover reservoir operation strategies under normal conditions. The listed questions were designed to be open, so that the water manager interviewed could freely explain what guides his release-decisions and the different characteristics of the system he has to consider. However, background theory on reservoir management (Beard *et al.* 1977; Draper & Lund 2004; Lund & Guzman 1999) as well as on the river basin model input variables (Hejazi *et al.* 2008; Ilich 2011) helped to ensure that the questions covered all aspects of the reservoir management theory that forms the basis of water resources simulation and optimization models.

The third category addressed more specifically reservoir management strategies for multi-purpose reservoirs, which present greater complexity in terms of operations. Moreover, some questions investigated historical changes in reservoir management strategies in order to understand whether the current operational guidelines are representative of past approaches or if they are more recent developments.

The fourth category was particularly important to address the research purpose. Indeed, the questions were formulated to identify the impact of different meteorological and hydrological conditions on the reservoir management approach with a particular focus on the factors that might initiate deviation from "normal" operations. The questions were developed to isolate the specific information on which the water mangers rely, because it could guide future development of optimization models that aim to match observable conditions with adaptive reservoir management strategies (Labadie 2004).

The questions pertaining to the fifth category were developed in order to elucidate the water managers' opinions on existing river-basin management models and the kinds of models they already use and trust. These questions are useful to help understand why reservoir managers tend to resist application of the output of computer-based optimization and simulation models to real-world reservoir operations as indicated in the literature (Black *et al.* 2014, Hejazi *et al.* 2008, Labadie 2004, Loucks & van Beek 2005, Simonovic 1992, Wurbs 1993; Yeh 1985).

The sixth category permitted collection of data that would help to address the third objective of the thesis, which concerns future trends in irrigation demands. Indeed, the questions permit quantification of the future possible expansion of the districts' irrigated land as well as report the crop mix changes observed.

Finally, the last category was developed to close the discussion in a positive manner and make sure the interviewee's final thoughts were reported. The complete list of interview questions within each of the seven categories that were designed to connect reservoir operators' practices with optimization model development can be found in Appendix A – Interview Questions.

4.1.4 Design Phase 4: How the data can be analysed?

The analysis of the interview data collected was accomplished through the "concept-driven coding process". This approach aims to identify patterns and similarities among the various information reported, and how these patterns could be associated with concepts identified in advance by the researcher (Brinkmaan 2013). In the present study, an example of a concept established before the analysis could be "actions taken in reaction to a drought" and each similar action mentioned by different interviewees will be identified or "coded" under this category. The concepts are first defined vaguely enough to permit analysis of the types of ideas reported without developing any preconceived perspectives on the answers that should be found, and are then refined in the analysis process. Following the same example, a new concept that emerged from the analysis process indicates that "rationing irrigators' water-uses is the preferred action adopted in reaction of a drought" and the interview data could be coded again under this concept.

The analytical process is iterative, since the first concepts identified are not sufficient to code all the different information gathered during the interviews. New concepts are therefore analysed as they arise either during the coding process or even during the interview work. Indeed, the interviewer can further clarify his/her understanding of the situation described by the interviewee by asking additional questions that might reorient the research toward a new conceptualization of the results. The initial list of concepts identified for this study prior to applying the coding process is analogous to the main themes addressed by the list of interview questions presented above. Finally, it is suggested to accomplish the data analysis and the interview process in parallel as elements from both can contribute to one another's successful development (Brinkmaan 2013). For example, the interview questions can be revised from one interview to the next.

4.2 Results and Discussion of the Interviews with Water Managers

4.2.1 Optimization Modelling *vs.* Cooperative Management

In Alberta's Water Act, senior licensees have the right to divert their full allocated volume of water before junior licensees divert any amount. If the allocated volume is greater than the licensee's capacity to divert water, the user's right to water becomes limited to the volume and rate his conveyance system is capable of carrying (Province of Alberta 2010). However, the data collected suggest that the seniority-based allocations of senior versus junior water users are not generally applied in real-world reservoir operations (BRID, LNID, MID, RID, SMRID and WID, personal communication, August-September 2014). Richard Phillips, the general manager of BRID, states that the water priorities are "meaningless" because no "priority call" has ever been made in the Bow River Basin. Similarly, Erwin Braun, the general manager of the WID, says that district personnel have discussed the sharing of river flows when there are shortfalls. In such cases, the districts with stored water have temporally reduced their water diversions from the river even if their license priority allows them to withdraw more. According to one interviewee, in times of shortfalls “one of us does not take its water, so the others can catch up” (EID, personal communication, September 2014), and another adds, “The principle is: if there are shortfalls, all the irrigation districts and irrigators share the shortfall evenly” (WID, personal communication, August 2014). Similarly for the Oldman River Basin, “even if SMRID has an older license, the district shares the water with the junior licenses in times of water shortage”, according to Jan Tamminga, SMRID’s manager of operations (Personal communication, August 2014).

In optimization models driven by unique water licence seniority rankings, real-world cooperation and more flexible diversion schedules employed by the irrigation districts are not captured. More realistic and probably optimal results could therefore be obtained under a better representation of basin-scale cooperation.

4.2.2 Reservoir management

4.2.2.1 Reservoir rule-curves

In practice, the irrigation districts assume that “every day is the first day of the next drought” (EID, personal communication, September 2014). Therefore, water managers aim to fill the district reservoirs as full as possible, as early as possible in the irrigation season (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August-September 2014). Indeed, for the first half of the irrigation season when the river stage is higher, the diverted water will serve two purposes: providing water for irrigation, and filling the larger reservoirs to their full capacity before the river stage decreases in late summer. The irrigation districts’ licences prescribe maximum withdrawal rates subject to the river flow (AEP, personal communication, August 2014). If the demand is greater than the licensed river withdrawals, reservoirs can be depleted; otherwise all the demand is met by diversions from the river. However, in late summer when the river is low, the irrigation districts can supply the irrigation demand by using the water stored in their reservoirs as they start gradually to deplete the reservoirs levels to the winter levels. In this way, the impact of irrigation on riparian and fish habitats is minimized.

The districts operate their smaller reservoirs as “balancing reservoirs” (TID, personal communication, September 2014), which means that they are used to supply existing demands until new water diversions from the river can refill them. These reservoirs thus improve the speed of delivery to most downstream users, and provide the district with more flexibility in the delivery of water. The irrigation districts refill smaller reservoirs first because their lower storage capacity increases the vulnerability of downstream users (EID, personal communication, September 2014), which differs from USACE's rule of "fill the higher (upstream) reservoirs first, and the lowest (downstream) last"; note that the aim of the USACE's rule is to maximize the amount of water available by minimizing spilling at the downstream end of the system (Lund 1996).

It could be noted that carry-over storage, from one year to the next, is limited since reservoir levels must be lowered during winter to prevent ice damage on reservoir structures and banks as well as allowing the districts to catch June's rain and the snowmelt runoff. The second objective of the winter level is of particular importance for multiple-purpose reservoirs used for flood control in addition to water supply. Even if the reservoirs are depleted for winter, there is still live storage available for the next year. However, in particularly dry years, the reservoirs could be depleted below their winter levels as the irrigation districts normally do not prioritize carry-over storage over meeting current demand. As a consequence, if the snow cover is lower than usual and if the spring is dry, the districts start the irrigation season with a lower supply (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August-September 2014). In such cases the districts "just hope for more water to come" (RID, personal communication, September 2014).

The actual practices in the irrigation districts interviewed are similar to the zone-based policy illustrated by Figure 14. Indeed, the water managers seem to maintain reservoir levels in an acceptable zone, which varies seasonally from summer to winter. Some multiple-purpose reservoirs have a water-supply and flood-control zone, while single-purpose reservoirs only have one target elevation based on the physical capacity of the reservoir.

4.2.2.2 Day-by-day management

Also important is recognition of the "day-by-day" approach adopted by all water managers interviewed, who will "never sacrifice today for tomorrow" (BRID, personal communication, August 2014). Districts' reservoir release decisions depend on today's water availability and today's water demand, and do not consider tomorrow's possible risks (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August - September 2014). There are recognized dangers to this approach: in 2000, SMRID let its irrigators use all the water they wanted while the river flows were low, which lowered the reservoirs more than usual before winter; the impact of dry conditions in 2001 was therefore worse.

Their philosophy was to use the water when there was a known economic value to be obtained from it, because they did not know the conditions for the next year. Thus, they adopt a rather passive approach. Toebes and Rukvichai similarly noted from their interviews with reservoir managers that daily operational deviations from the established rule-curve are not related to previous release decisions: "the plots should not be given any cumulative interpretation" (Toebes & Rukvichai 1978). In terms of modelling, this approach correlates well with the "single time-step optimization (STO)" method used in most river basin models, which optimizes allocations at each simulation time-step without considering future or past allocations (Ilich 2011).

4.2.2.3 Medium-term planning

In order to minimize the losses in their reservoir systems and operate their hydraulic structures with minimal adjustment, the irrigation districts anticipate their water supply *versus* water demands (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August-September 2014). Indeed, even if the districts base their operations upon delivery requests (the water demands from irrigators), experience helps district "ditchriders" (those in charge of water delivery to the farm gate) and the district in general to anticipate demands and the losses by evaporation and seepage (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August-September 2014). Further, an interviewee explained that his district seeks to identify future trends in crop mix to schedule better the refill and draw down periods of its reservoirs, as some crops (such as seeds) require early moisture, while other crops require late irrigation (such as corn). When assessing future water demands and water supply, districts must coordinate their withdrawals with upstream and downstream users along the river reach and take into consideration the time of travel of the water (BRID, EID and WID, personal communication, August-September 2014), which can be as much as a week (SMRID, personal communication, August 2014).

4.2.2.4 Information used in operational decision-making

In their daily operations of reservoirs, water operators base their decisions on different information. As explained by an interviewee, "any time you can gather more information to help you feel more comfortable with your decisions, it is better". The major information sources used by the irrigation districts include,

- Water orders from the irrigators;

- River flows (each water licence is subject to diversion rates that vary according to the river flows);
- Actual reservoir levels;
- Weather forecasts (temperature and precipitation for the next week);
- Soil moisture reserves (general information provided by the irrigators);
- Actual flows in the conveyance system;
- Recorded flows previously delivered to the irrigators;
- Theoretical irrigation scheduling tools, such as the Alberta Irrigation Management Model software provided online by AARD (2015).

In addition to information on current conditions, another important factor is the human dimension: the capacity of district staff to work closely with the irrigators as they can communicate easily with irrigators and can react quickly when necessary (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August-September 2014).

4.2.3 Drought Mitigation

4.2.3.1 Water supply forecast

The irrigation districts also use data for planning the irrigation season before it starts. Every year before spring, the Government of Alberta forecasts the available water supply for irrigation by using the following data:

- Snow pack monitoring in the Rocky Mountains, upstream of the irrigation districts;
- Actual winter storage in the reservoirs;
- Soil moisture values provided by AAF;
- Normal, seasonal rainfall volumes.

This information is published online and is used by the irrigation districts to determine whether they should plan for rationing at the beginning of the season. They advise irrigators of conditions via newsletters or at annual meetings in the spring (BRID, EID, LNID, MID, RID, SMRID, TID and WID, personal communication, August-September 2014). The Government of Alberta reviews the estimation of the water supply every month during the growing season by updating the forecasts with actual data. The irrigation districts can then decide whether to maintain or remove the "rationing mode" (LNID, MID, RID, SMRID and TID, personal communication, August-September 2014). The irrigation districts also follow snowpack data, as it is a good indicator of conditions at the beginning of the season (BRID, EID and WID, personal communication, August-September 2014). Indeed, for the Bow River Basin, average snow depth values in the Rocky Mountains indicate roughly whether enough water will be available for diversion from the river to meet irrigation demands and to fill reservoirs up to the end of June (BRID and WID, personal communication, August 2014).

4.2.3.2 Water rationing

As mentioned previously, water managers do not apply annual or inter-annual water deficit-distribution strategies, but instead impose water rationing for all irrigators at the beginning of a growing season. Each district decides on a maximum water allocation for normal to wet years, when no rationing is necessary; this allocation varies from 17 inches (RID) to 24 inches (BRID), or about 430 to 610 millimetres (mm), based on districts' water storage capacity and distribution efficiency. However, some districts typically allow irrigators to divert more than the prescribed limit, as the majority of the irrigators will not use their full allocation (EID, SMRID and TID, personal communication, August-September 2014). In dry years, the allocation can be reduced to as low as 7 inches (about 180 mm) and is maintained more strictly for all users (SMRID, personal communication, August 2014). The rationing limit is based on the probable volume of water available for the season, which varies for every district. In addition to application limits for individual irrigators, districts can have drought plans that extend to other users. For example, if EID had to apply water rationing for irrigation, the municipalities and other water users that withdraw water from EID's canals would have to reduce their consumption equally to share the shortage, with no differentiation between junior and senior users (EID and RID, personal communication, September 2014).

Water rationing was implemented in the three irrigation districts of the Bow River Basin after the drought of 2001. During that year, other water cut-off strategies were applied: the EID cut all water diversions for two weeks just before the end of the season (in September) to refill its reservoirs (EID, personal communication, September 2014) and the WID imposed a rotation scheme that restricted the use of pivots to only one at a time (WID, personal communication, August 2014). In contrast, the BRID did not impose irrigation restrictions, and the media contributed to establishing a panic around the district, which caused irrigators to try to store soil moisture for the next year and unnecessarily depleted the reservoirs (BRID, personal communication, August 2014).

Under rationing, the irrigation districts indicated that irrigators set their own management strategy before the start of the irrigation season by growing crops that require less water, applying water earlier in the season in order to store water in the soil, or transferring the water normally applied to low-value crops to high-value crops only. In the irrigation districts of the Oldman River Basin, another adaptation strategy explored in 2001 was the sale of water between irrigators and other water users under formal authorization.

These findings contrast with theoretical optimization methods, which aim to distribute the water deficits over a predetermined simulation time without considering irrigator's actual strategies at the beginning of the growing season. Indeed, the districts' release policies could be compared to the hedging rule policy (see Figure 15), with the difference that it is not the released water that is temporarily reduced as a water conservation strategy, but rather the target demand (D) that is reduced. Therefore, approaches like "multiple time-step optimisation (MTO)", which aims to derive optimal reservoir rule curves based on perfect foreknowledge of water supply and water demand (Ilich 2011), should ideally incorporate early season adaptations as well. Of course, it is possible that the actual practices described above are non-optimal, compared with modelling results that are obtained without irrigators' adaptation strategies; however, an understanding of water managers' perspectives is nonetheless informative.

4.2.4 Summary of the Interview results

Interviews with irrigation district water managers demonstrated that their water management strategies for different climatic and hydrological conditions combine experience with adaptability. The innovative contribution of these research findings is to provide real-world data and a better understanding of water managers' perspectives on reservoir management. The results suggest that the rules behind water allocation modelling in the Albertan context should be oriented toward 1) basin-scale cooperation, 2) accounting for the effects of early-season water rationing at an on-farm level, and eventually 3) day-by-day release strategies if computer modelling capacity permits optimization of reservoir releases on a daily time-scale. However, the third conclusion presents difficulties, since even though optimization of the day-by-day reservoir releases would present great advantages from an operational perspective, the large data requirements, uncertainty in future climatic conditions, and a necessary ten-fold increase in computational complexity in the optimization algorithm are likely to eliminate its potential benefits. Future research work in the optimization field should thus concentrate its effort on the first and second conclusions presented. The actual management practice during a drought consists of managing by cooperation and reducing water demands early in the season rather than in the application of licence priorities or water supply hedging. Therefore optimization models should evaluate whether more efficient water storage management could ensure enough water or if actually-preferred early-season adaptations lead to optimal water-use.

Although this study took place in southern Alberta, the methodology presented here is likely to help modellers from other regions of the world to conduct similar investigations in order to better understand water managers' behaviours in the context of competitive water-uses.

5. Simulation Work

Simulation work was necessary to assess the second and third objectives of this research project, which were to evaluate the irrigation outlook of alternative reservoir management strategies in the BRID and different scenarios of irrigation development under dry to wet conditions. Water allocations in the SSRB were modelled through the use of the Water Resource Management Model (WRMM) and the water irrigation demand with the Irrigation Demand Model (IDM).

The following sections describe the modelling methodology, as well as the scenarios simulated, the performance criteria for assessing model output and the selection of years that represent dry to wet conditions. Finally, the simulation results and discussion are presented.

5.1 Simulation Methodology

5.1.1 WRMM Modifications

The WRMM model simulates water supply and water demand in the entire SSRB. However, due to the complexity and size of the SSRB, there are a total of seven sub-models run separately whose outflows and inflows maintain the water balance of the entire system. The sub-models are: the TransAlta Utilities, Highwood Diversion Plan, Southern Tributaries, Special Areas Water Supply Project, Acadia Project, Milk River Basin and the Main SSRB (Alberta 2010); the Main SSRB model receives inflows from- or supplies water to all the sub-models except from the Milk River Basin simulation as shown in Figure 17. For this thesis work, only the Main SSRB model was used as it simulates the Bow River Basin, where the BRID is located. The Main SSRB model is at the heart of four sub-basin confluences: the Bow River below Bearspaw Reservoir as well as the Red Deer, Oldman and South Saskatchewan Rivers. These sub-basins are managed jointly to meet the Apportionment Agreement at the Saskatchewan border. Please note that, for simplicity, the Main SSRB model is identified simply as the WRMM in this thesis.

In order to analyse the current reservoir operations simulated by the WRMM and to develop reservoir management alternatives for the BRID, the following steps were applied and are further described:

1. Compare the BRID's reservoir operations simulated in the Original WRMM with the BRID's actual reservoir operations from the interview data;
2. Modify the BRID's reservoir rule curves in the WRMM in order to increase the realism of the model results by a better representation of the BRID's actual reservoir operations;

3. Change the penalty associated with the BRID's reservoir operating zones to assess whether improved results can be obtained from simulation of the optimal penalty settings suggested by the literature;
4. Modify the BRID's reservoir rule curves to simulate other operation alternatives and evaluate their benefits.

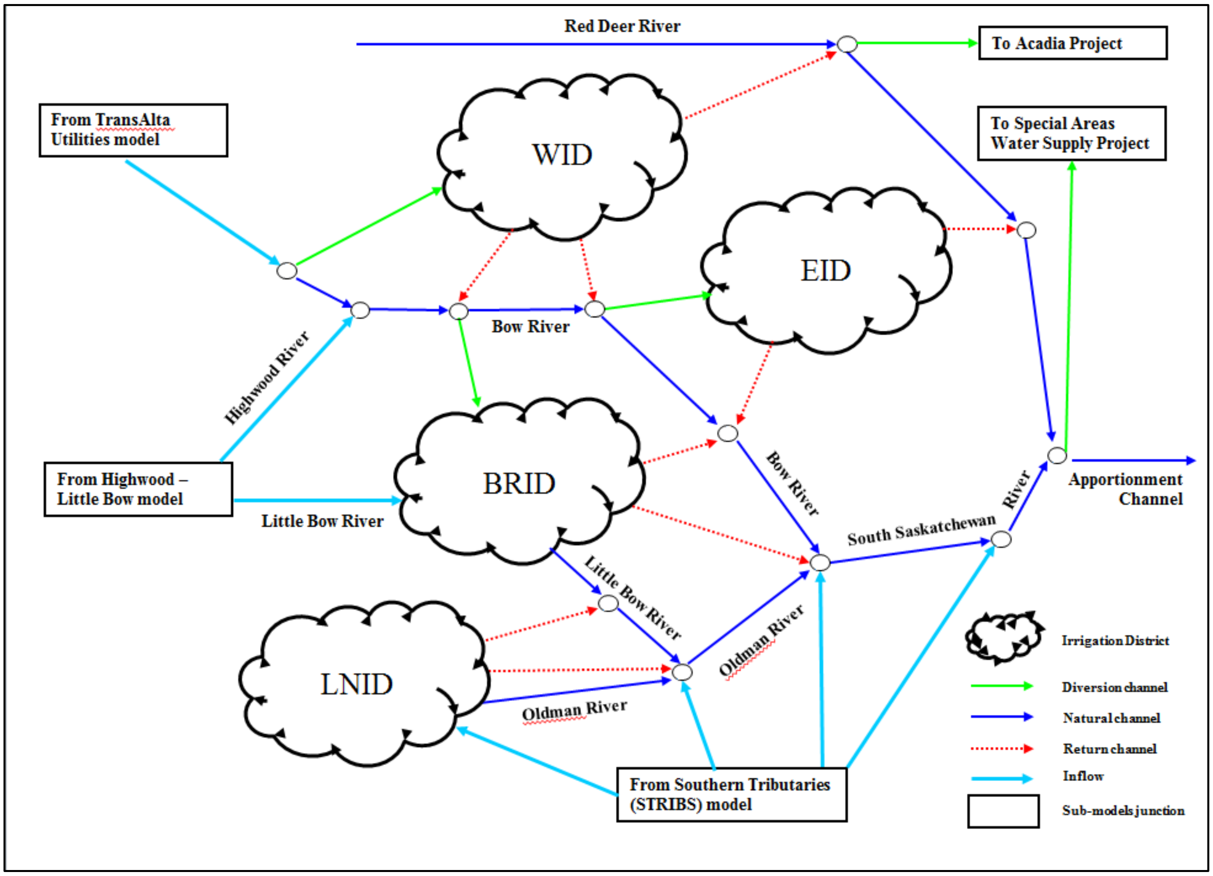


Figure 17: WRMM Sub-model Junctions with the Main SSRB Model

5.1.1.1 Modelling the BRID's Reservoirs in the WRMM

The following section presents an overview of BRID's infrastructure and how it is represented schematically in the WRMM, as well as the penalty scheme defined in the model to allocate the water among the different components of the district.

Figure 18 presents a map of the BRID on which the main canals and reservoirs of the district are indicated while Figure 19 gives the schematic of each BRID's reservoir and irrigation blocks simulated in the WRMM. The BRID's irrigators are well supported by reservoirs as all the BRID's irrigation blocks representing irrigation demand of the district in Figure 19 are located downstream of at least one of the BRID's reservoirs: McGregor, Travers-Little Bow, Badger, and Scope. The BRID's licence and other licences supplied by the district's network are defined on the diversion canal connecting the Bow River with McGregor Reservoir, the district's most-upstream reservoir. More particularly, the licences' specifications are simulated between the nodes 9 and 28 of Figure 19 – nodes are marked as circles, while river channels and district conveyance structures are marked as lines with arrows in the direction of flow, called arcs. In the WRMM, licences can be simulated using diversion canals whose maximum flow capacity will be set as the licence maximum rate. The BRID's conveyance system also provides water to multiple private users; therefore, a number of diversion canals are necessary to represent their individual licences. In reality, only one canal is used to carry the water from the Bow River to McGregor reservoir (Carseland canal). The canals upstream of node 9 (arc 420) and downstream of node 20 (arc 425) ensure that the total flow diverted at the Bow River junction is in accordance with Carseland canal capacity and the total maximum permissible diversion rate.

Some of BRID's reservoirs have particular characteristics. Travers-Little Bow reservoir is an ongoing project to combine the Travers and Little Bow reservoirs. The WRMM model has been modified by AEP staff to simulate this future configuration of the district as the construction work of the Travers-Little Bow should be completed for the 2017 season. Travers-Little Bow reservoir is termed an on-stream reservoir as it receives water from the Little Bow River. It serves the two purposes of water supply for the BRID and flood control for the Little Bow River. Unless there is a flood, Government policy is that all water coming from the Little Bow River is passed downstream and is not used or stored to supply the BRID's irrigation demand. Lost Lake is an unusual reservoir that receives a portion of the return flows of the district because it is located at a lower elevation. The water is pumped out of this reservoir only when it reaches a maximum level. As the water quality is poor, irrigators usually don't irrigate when the water from Lost Lake is pumped out and carried by the canal to the downstream junction with the Bow River. Both McGregor and Travers-Little Bow are owned by the government of Alberta but are operated by the BRID under the Government's directives. They are often described as the BRID's external reservoirs. All other reservoirs are owned and managed by the BRID and are considered the BRID's internal reservoirs.

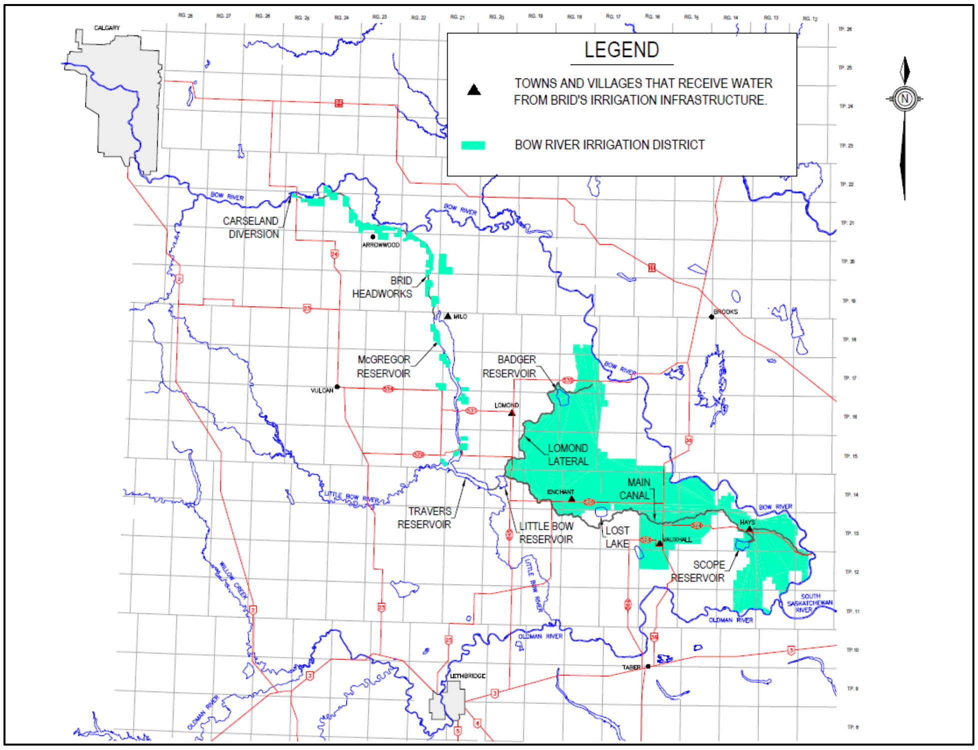


Figure 18: Map of the Bow River Irrigation District (BRID 2014)

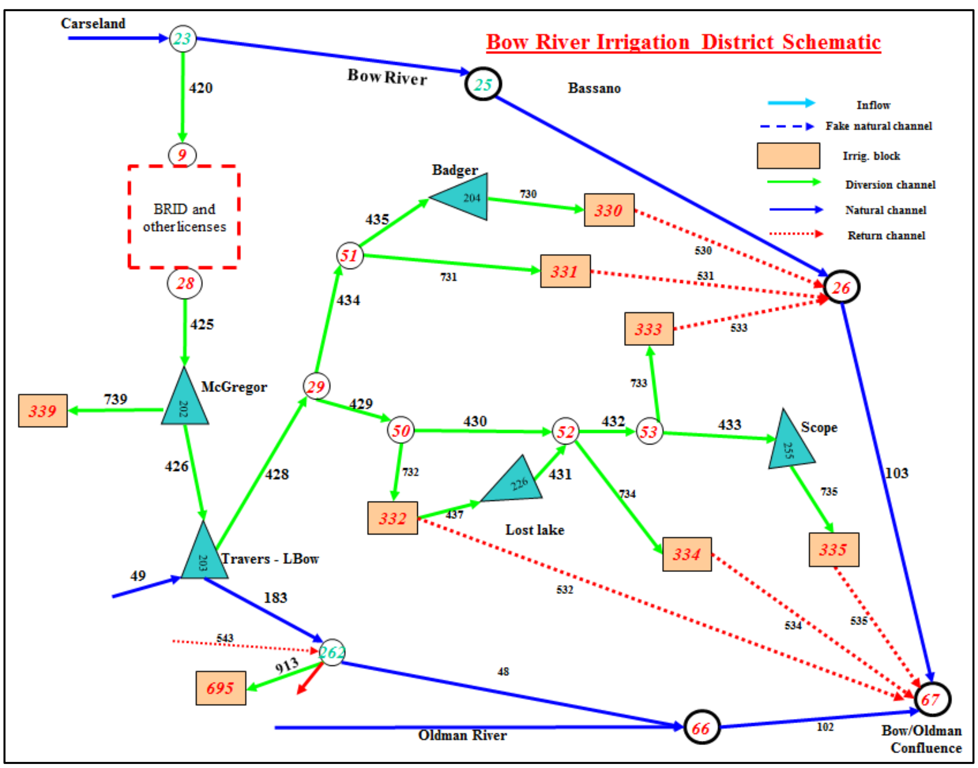


Figure 19: Bow River Irrigation District as Simulated in the WRMM (Reza Ghanbarpur, AEP, personal communication, November 2014)

As previously explained in the Chapter 3, the water allocation produced by the WRMM is a function of the license priority for each water licensee and the system components represented under a penalty-point scheme. More specifically, the reservoir operations are guided by an ideal storage curve and zones above and below the ideal curve, which are defined for each reservoir simulated. In general, the penalty for being above or below the ideal curve will increase as the distance from the ideal curve and the simulated storage level increases. The Simulation Control File (SCF) specifies all reservoir ideal curves, storage zones and penalties. In optimization terms, the total penalty cost in a simulation increases the farther a reservoir's level is from its ideal storage curve and when an irrigation block does not receive its full irrigation demand. Normally, a higher penalty is associated with irrigation blocks, as it is preferable to avoid water deficits by using stored water – and consequently lowering a reservoir under its ideal storage level. Other penalties could also represent the minimum flow to be maintained in a canal, diversion structure or river reaches. A complete description of the WRMM components and files can be found in the Computer Program Description: Water Resources Management Model (Alberta Environment 2002).

Figure 20 presents a generic set of operating zones for reservoir operations in the WRMM. Here, the reservoir has two zones above its ideal curve: a spill zone and flood control zone as well as four zones below its ideal curve: 1st, 2nd, 3rd, and 4th relaxation zones representing four levels of water conservation. The storage elevation of the different zones can vary over the simulated cycle as a function of the time of the year: Figure 20 illustrates monthly variation of the reservoir operating zones. In the WRMM, the changes in storage elevation are indicated in Julian days and the model linearly interpolates between two points to draw reservoir operating curves. The lowest zone could represent the dead storage of a reservoir or might be assigned for maintaining a minimum storage level for water quality or other purposes. As a result, the model aims to keep the reservoir level between maximum and minimum values that do not necessary represent the designed live storage. If the minimum operating level is not the dead storage of a reservoir, the storage-elevation curves or the elevation-outflow curves of the reservoir, as indicated in the SCF file, should be designed to ensure that the reservoir is not drawn down below its physical limit. In the case of the Figure 20, the 4th relaxation zone corresponds to the dead storage as the reservoir outlet, which is represented by the black rectangle break, is located above it.

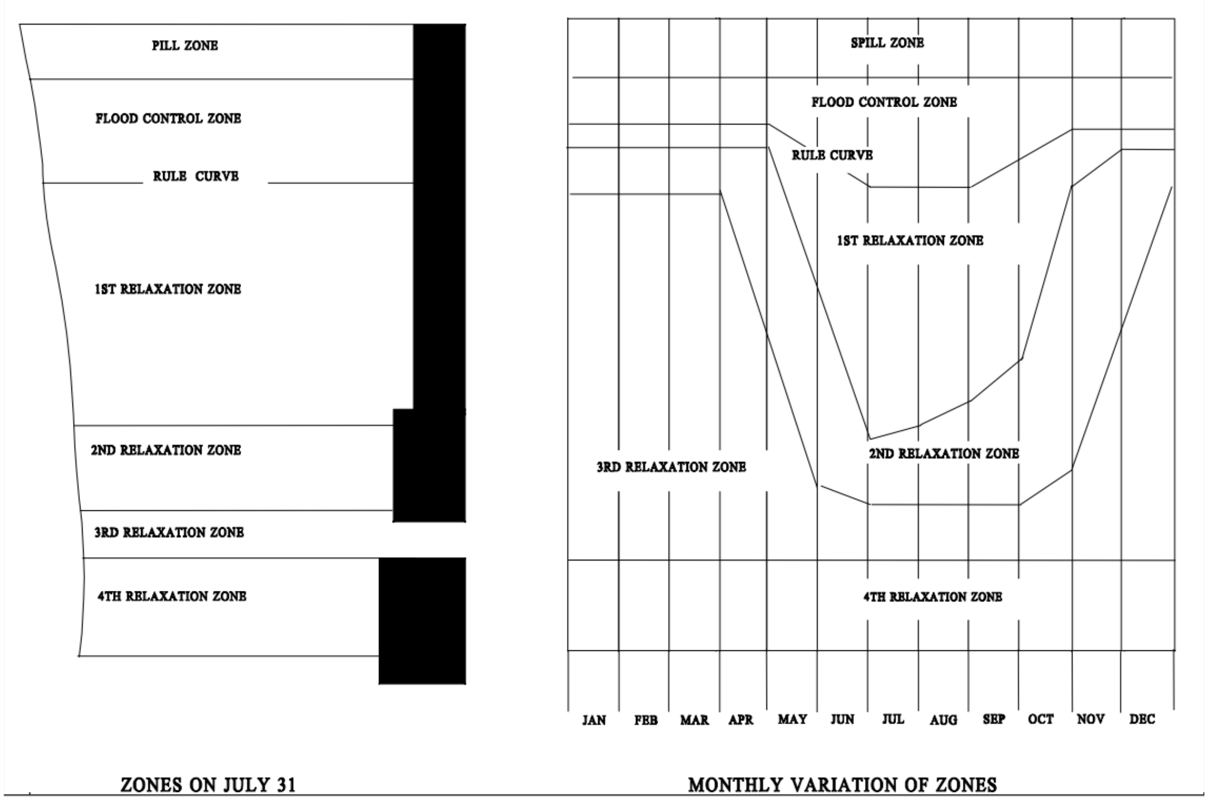


Figure 20: WRMM's Reservoir Storage Penalty Zones (AESRD 2012)

Figure 21 gives an example of the penalties that could be allocated to different interconnected components of the model: a reservoir with three zones below its ideal curve, a water licence for a water demand that is constant over the year and a river reach that has various instream flow requirements according to the time of the year. For the example illustrated by Figure 21, the WRMM would lower the reservoir level from the ideal curve to the upper limit of the second storage zone (penalty 1) before cutting the water supply allocated to the license (penalty 5). However, the model could supply only a portion of the licensee's demand to keep the reservoir above its second operating zone or to maintain the instream flow requirements, because their penalties are higher than the one associated with the water licence. Moreover, the reservoir could be lowered to its second operating zone (penalty 6) to meet the instream requirement downstream (penalty 7). Finally, considering the system components shown in Figure 21, the reservoir would not be emptied by the model to its third operating zone as it would generate the highest penalty for doing so (penalty 9). Such a high penalty may apply, for example, if the lowest operating level represents the dead storage of the reservoir; the penalty should be high enough to impede reservoir drawdown below the dead-storage elevation.

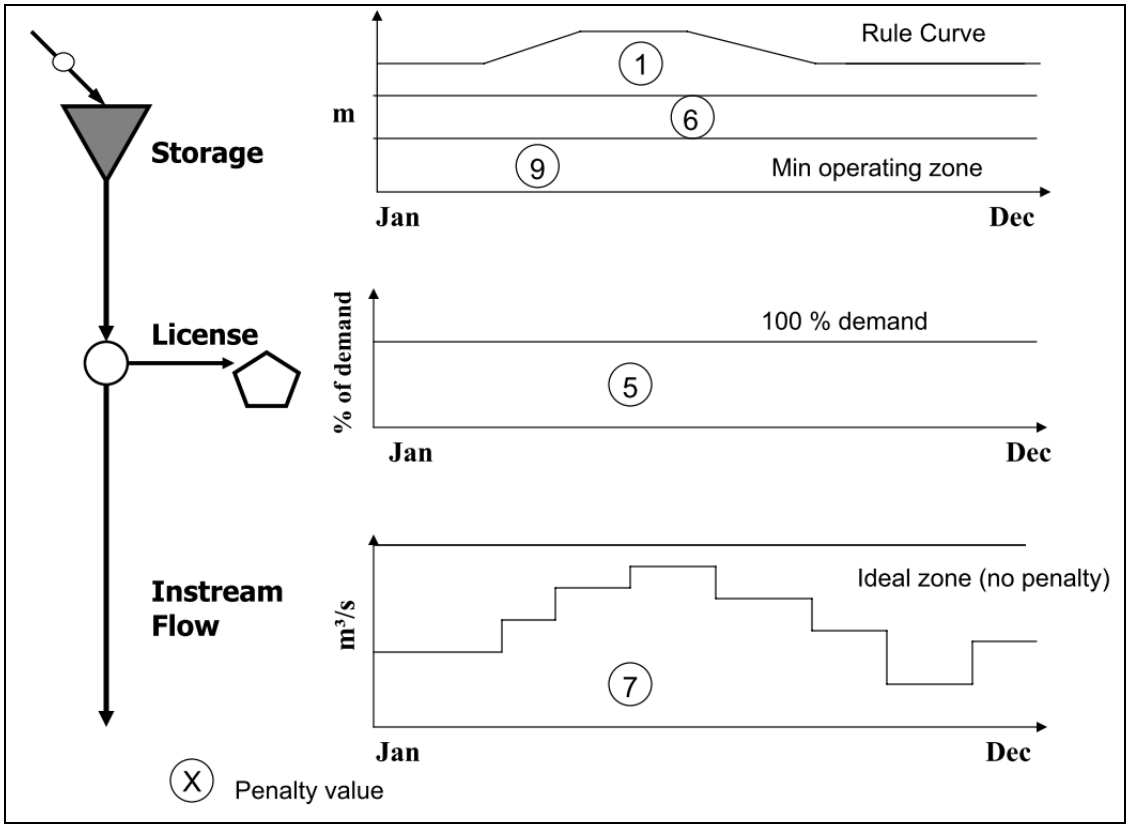


Figure 21: Example of Zones and Penalties Representing WRMM's Priorities (AESRD 2012)

5.1.1.2 Comparison of the BRID's Reservoir Operations: WRMM versus Interviews

As reported during the interviews with the BRID's manager and water controller (Richard Phillips and Dave Cholka, personal communication, BRID, August 2014), the BRID's reservoirs are usually filled at the beginning of the irrigation season to their ideal summer level and then operated between a minimum operating level and the ideal summer level. Reservoir levels must be lowered during winter to prevent ice damage on the reservoir structures and banks, as well as to allow the districts to catch June's rain and snowmelt runoff. If the district is not short of water, the reservoir levels should stay close to the ideal summer level and are gradually reduced to their ideal winter level at the end of the irrigation season. If the water is scarce, the reservoirs might be depleted throughout the irrigation season to meet the demand and the winter level may not be reached. For simplicity, the period during which the reservoirs are maintained at lower levels is called the winter period and the period during which the reservoirs are managed for irrigation is called the summer period, even if the irrigation season includes part of the spring and fall seasons and the non-irrigation period also extends beyond the winter season. Table 4 presents the ideal summer and winter levels as well as the minimum operating levels of the

BRID's main reservoirs. Interview data and WRMM data are compared, and reveal that several operational changes were not captured in the original WRMM settings – indeed, there are very few matching values. For example, some of the BRID's reservoirs have experienced bank erosion over time, or have new operating objectives to mitigate flooding, which have influenced their operations.

Table 4: BRID's Reservoirs Operating Levels from BRID Data and WRMM Data

Reservoir	Type of Data	Ideal Summer Level (m)	Ideal Winter Level (m)	Minimum Operating Level (m)
McGregor	Interview	874.10	873.56	865.63
	WRMM	874.38	873.56	871.74
Travers-Little Bow	Interview	855.50 - 856.18	854.06	851.00
	WRMM	856.18	854.06	850.20
Badger	Interview	823.50	823.00	822.80
	WRMM	824.00	823.50	823.00
Scope	Interview	786.54	785.47	785.32
	WRMM	786.61	785.81	785.31
Lost Lake	Interview	784.50	783.80	783.65
	WRMM	784.00	783.80	783.50

The actual ideal summer level of McGregor is lower than the level indicated in the WRMM, since McGregor is now maintained at a lower elevation (874.10 metres) to protect its banks and encourage development in the area surrounding the lake. Moreover, some irrigators pump their water from McGregor reservoir directly and cannot irrigate if the reservoir elevation falls below 871.65 metres. To account for this peculiarity, the WRMM model sets the minimum operating level of McGregor to 871.74 meters (m) instead of its real dead storage level of 865.63 meters. During the interview, the BRID general manager stated that the BRID would not hesitate to draw down McGregor reservoir to meet district irrigation demands, despite the effect on irrigators diverting directly from McGregor reservoir. Indeed, their demand represents only a small portion of the total district demand: only about 1% (R. Phillips, personal communication, BRID, August 2014). In their study, Sheer *et al.* (2013) also reported that the dead storage of McGregor reservoir was defined in the WRMM as the level at which one irrigator could no longer divert water from the system instead of the actual dead storage level. In response, AEP indicated that the real dead storage of McGregor is specified in the WRMM by the elevation-outflow curves defining McGregor's outflow rate. In their simulations, AEP prefers to maintain McGregor reservoir above 871.74 meters using this value as the minimum operating level in order to penalize all the BRID`s irrigators equally if there is a shortage in water and to mitigate the water deficits of back-to-back drought years as the storage available for the second year would be higher than if the reservoir had been depleted (Tom Tang, personal communication, AEP, July 2014). Similarly, Badger and Scope reservoirs have experienced bank erosion, which has obligated the district to operate them slightly lower in summer and in winter. Again, these differences in maximum operating level and ideal summer and winter levels were not captured in the WRMM reservoir settings.

The Travers-Little Bow operating levels reported during the interview are based on Travers reservoir operations, and it is likely that the future Travers-Little Bow reservoir will be operated under the same rules (Richard Phillips, personal communication, BRID, August 2014). The current ideal summer level for Travers-Little Bow is 855.50 meters until late June with an increase to 856.18 meters for the remainder of the summer. The lower target-elevation for the first half of the summer was developed for flood mitigation purposes and was not included in the WRMM. Moreover, the minimum operating levels input in the WRMM for Travers-Little Bow reservoir is 850.20 meters, which is below the actual dead storage of the reservoir of 851.00 meters.

Lost Lake has a dead storage level of 783 meters and a full supply level of 784 meters; however, BRID maintains the reservoir between 783.65 meters and 784.50 meters to increase its evaporation rate and reduce the need to pump out the reservoir.

The reservoirs are usually drained gradually to their winter levels at the end of the summer until approximately mid-October (after the Thanksgiving long-weekend), and are refilled to their summer levels as soon as possible after the winter (between April and May). The refill date depends principally on the condition of the diversion canals, which need to be ice-free before water can be safely diverted. The timing of the snowmelt runoff is also important since it increases the river stage, and therefore the permissible river diversions rates. Table 5 presents the refill and drawdown schedule as indicated in the WRMM. Note that because the WRMM linearizes reservoir operating levels between two data points, Table 5 indicates the last date at which the winter level is ideally maintained and the date at which the summer level is ideally reached by the model (Refill Period). Similarly, Table 5 indicates the last date at which the summer level is ideally maintained and the date at which the winter level is ideally reached by the model (Drawdown Period). As indicated in Table 5, the reservoir operation schedule is close to the one indicated through the interviews with the BRID. The only difference is for McGregor Reservoir, which is depleted to its winter level over a short period of time in August, while in reality, the reservoir starts to be depleted in mid-July and typically reaches its winter level more gradually into October.

Table 5: WRMM's Reservoirs Refill and Drawdown Schedule in the WRMM

Reservoir	Refill Period		Drawdown Period	
	(Julian day)	(Date)	(Julian day)	(Date)
McGregor	100-110	April 10th – April 20th	232-243	August 20th – August 31st
Travers-Little Bow	100-120	April 10th – April 30th	206-288	July 25th – October 15th
Badger	90-151	March 31st – May 31st	243-288	August 31st – October 15th
Scope	90-151	March 31st – May 31st	243-288	August 31st – October 15th
Lost Lake	90-151	March 31st – May 31st	243-288	August 31st – October 15th

Table 6 compares the live storage of the main BRID reservoirs in the published data of AARD (2014b) with the interview results and the WRMM original settings. The values published by AARD (2014b) are based on the initial reservoir live-storage volumes. The values representing the BRID's current management are calculated from the interview data, which take into account recent erosion problems or practical operating requirements. Indeed, they represent the storage available between the minimum and maximum operating levels specified by the BRID and reported in Table 5. In the case of Badger, two types of storage are reported in addition to the district's current operating storage. Badger has a total storage of 51,313 cubic decameters (dam^3) of which only 13,568 dam^3 could originally flow out by gravity, while the remaining storage needed to be pumped out, which would generate significant costs. As a result, the water stored under the "freely flowing" level has never been used by the district. The current supply indicated (5,725 dam^3) is the storage available by gravity under the actual erosion restriction.

The live storage calculated from the WRMM data is based on the difference in storage between the ideal water level in summer and the lower operating level, as specified by the penalty zones. The storage value is estimated by interpolation using the WRMM storage-elevation curves. The BRID also operates other smaller reservoirs, which are not simulated in the model: Reservoir "D" has a storage capacity of 350 dam^3, Reservoir "H" has a capacity of 2,790 dam^3, and Reservoir "PFRID" has a volume of 560 dam^3 (AARD 2014b).

Table 6: BRID's Reservoirs Live Storage from AARD Published Data, BRID Data and WRMM Data

Reservoir	AARD (2014b) (dam^3)	BRID's Current Management (dam^3)	Original WRMM (based on Penalty Levels) (dam^3)
McGregor	351,060	337,330 [1]	127,580
Travers-Little Bow [2]	-	150,000	153,694
Badger	57,120	5,725 [3] (current operational supply) 51,313 [3] (total designed supply) 13,568 [3] (gravity designed supply)	9,396
Scope	12,930	7,191 [4]	7,645
Lost Lake	5,060	4,659 [5]	1,941

[1] Based on McGregor reservoir surveying data reported to BRID by AEP (2004)

[2] Travers-Little Bow Reservoir is a combination of Travers and Little-Bow reservoirs scheduled for spring 2017. Therefore, AARD has not published the live storage of this combined reservoir. The live storage value indicated from BRID interviews is an approximate value.

[3] Based on Badger reservoir storage-elevation curve graph reported to BRID by Acres Consulting Services Ltd.

[4] Based on Scope reservoir storage-elevation curve graph

[5] Based on Lost Lake reservoir storage-elevation curve graph reported to BRID by Ducks Unlimited

The main difference between the values reported in Table 6 concerns McGregor storage, which is considerably reduced in the WRMM. Indeed, even if the WRMM allows McGregor reservoir to be filled to its full supply level (874.38 meters) rather than to the current permissible level (874.10 meters), the artificially high minimum operating level (871.74 meter) reduces by more than half the simulated storage available, compared with the value reported by the BRID or by AARD (2014b). Moreover, the WRMM seems to overestimate slightly the storage that would be available through the combination of Travers reservoir with Little Bow reservoir compared to the future storage estimated by the BRID. However, as the combination of Travers reservoir with Little Bow reservoir is not yet complete, it is difficult to judge how far apart the simulated and real storages will be. Note also that the minimum operating level set in the WRMM is lower than the actual dead storage as shown in Table 4, which also has an impact on the total storage available for Travers-Little Bow reservoir. Badger storage is smaller than the value published by AARD (2014b) as a consequence of the gravity supply level. The difference between the actual and modelled supply is a consequence of the bank erosion, which required a reduction of its current available volume. Simulated storage for Scope is relatively close to the value estimated from the interview data and the difference is also related to the changes in operation. Finally, the difference in Lost Lake storage is considered to have a negligible impact, as this reservoir does not supply irrigation demands and its volume is relatively small compared to the total storage capacity of the district.

5.1.1.3 WRMM Modifications to Simulate Current BRID Reservoir Operations

Considering the difference in summer and winter operating levels between the original WRMM setting and the BRID current management, the WRMM was modified to generate more realistic results. Table 7 presents the available storage for water supply if the BRID's reservoir ideal curves are updated in WRMM. Moreover, the table presents the combined effect of simulating in the WRMM the current minimum operating level of BRID's reservoirs in addition to updating their ideal curves.

Table 7: BRID's Reservoirs Live Storage from Changed WRMM Settings

Reservoir	**Updated Ideal Curves**		**Updated Minimum Operating Zone and Ideal Curves**	
	Operating Levels Changed (m)	**(dam^3)**	**Operating Levels Changed (m)**	**(dam^3)**
McGregor	874.38 → 874.10 (Summer)	113,425	871.74 → 865.63	336,304
Travers-Little Bow	856.18 → 855.50 [1] (Summer)	153,694	850.20 → 851.00	135,859
Badger	824.00 → 823.50 (Summer) 823.50 → 823.00 (Winter)	4,698	823.00 → 822.8	6,577
Scope	886.61 → 886.54 (Summer) 885.81→ 885.47 (Winter)	7,212	-	-
Lost Lake	884.00 → 884.50 (Summer)	4,836	883.50 → 883.65	4,253

[1] Only up to the end of June (Julian day 181); thereafter, the ideal summer level is again 856.18 meters

Based on the results presented in Table 7, it was considered unnecessary to change the minimum operating level of Travers-Little Bow reservoir as it would produce an available storage considerably below the one estimated from the interview data. Similarly, Badger's minimum operating level was not changed, as in this case the WRMM would slightly overestimate the available storage. In addition, because AEP had always used the artificially high minimum operating level of McGregor (871.74 meters) rather than its dead storage level (865.63 meters), for this research it was recommended to compare the modelling results obtained from both version of the WRMM; one using a minimum operating level of 871.74 meters and another using the actual dead storage level of 865.63 meters. As a result, three additional SCF files were created in addition of the original SCF file used to run the WRMM. The four WRMM versions are described as follow:

1. The Original WRMM represents the original WRMM setting as used by AEP staff;
2. The McGregor Dead Storage represents the original WRMM setting but with the real dead storage level as the minimum operating zone for McGregor;
3. The Updated Ideal Curves WRMM represents an updated version of the WRMM in which the BRID's reservoir ideal curves were modified to represent the district current operations under bank erosion, flood mitigation or other real operational practices, but McGregor's minimum operating level remains the elevation at which irrigators start to have pumping difficulties rather than at its real dead storage level;
4. The Current Management WRMM represents an updated version of the WRMM in which the BRID's reservoir ideal curves and McGregor minimum operating level were modified to represent the district current operations as well as McGregor's total available supply.

In the case of the Current Management version, the penalty associated with the irrigation block diverting water directly from McGregor reservoir needed to be adjusted. In Figure 19, this block is identified as the block 339. If McGregor reservoir is drawn down below the minimum elevation at which the irrigators can pump water, the irrigation block demand should not be supplied by the model. This threshold elevation was specified as 871.65 meters by the BRID but is defined as 871.74 meter in the WRMM. In order to produce conservative results in terms of possible water deficits, the threshold value was kept at 871.74 meters. Accordingly, the lower limit of the second relaxation zone was set to 871.74 meters and the lower limit of the minimum operating zone was changed to the actual dead storage level of 865.63 meters in the Current Management version. The penalty of the irrigation block 339 was changed to 1240 instead of 1245 and the minimum operating zone penalty was maintained at 1248. The block 339 irrigation demand will thus be cut by the model before McGregor Reservoir level goes below 871.74 meters. The Computer Program Description: Water Resources Management Model (Alberta Environment 2002) could be consulted for additional information on the reservoir operating zones and penalties in the SCF. Figure 22 to Figure 26 presents the original WRMM reservoir operating zones (solid lines) as well as the curves modified in the updated versions of the WRMM (dashed lines).

McGregor and Travers-Little Bow reservoirs have five operating zones: one flood control zone above the ideal curve, 1st relaxation zone below the ideal curve, 2nd relaxation zone below the relaxation zone curve and 3rd relaxation zone below the minimum operating level, which can be seen as the dead storage in the case of Travers-Little Bow reservoir. In the case of McGregor, its minimum operating level is either the block 339 minimum level for diverting water in the Original WRMM version or the dead storage level in the Current Management version.

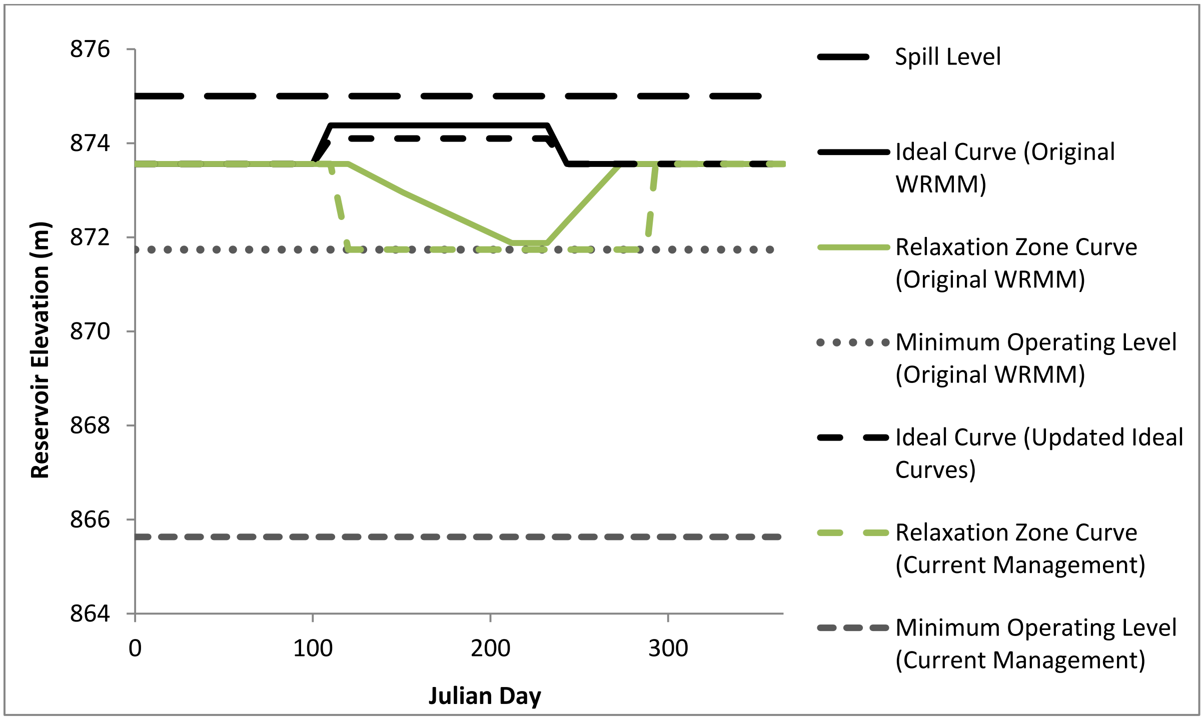


Figure 22: McGregor Operating Curves in the Original WRMM, Updated Ideal Curves, Current Management, and McGregor Dead Storage WRMM versions

The ideal curve simulated for the Updated Ideal Curve scenario is the same as the one simulated for the Current Management scenario. Similarly, the minimum operating level for the Current Management scenario is the same as the McGregor Dead Storage scenario. Moreover, the relaxation zone curve of McGregor reservoir for the Current Management scenario was reduced in summer to maintain the physical constraint applicable to the water diversions of the block 339 and represented through the penalty point scheme. For the rest of the year, the relaxation zone curve was maintained at the same elevation specified in the Original WRMM, which is the ideal winter level. During winter, the ideal curve and the relaxation zone curve are exactly the same. This means that the model will prioritise reaching the winter level at the end of the growing season in comparison to reach the ideal summer level during the irrigation season, because the penalty to lower a reservoir below the relaxation zone curve is higher than to deplete it below the ideal curve. McGregor's drawdown and refill schedule was kept as the one simulated in the Original WRMM. The only exception is for the relaxation zone curve that is maintained lower for all the extent of the irrigation season in order to ensure that the Block 339 has access to water when needed. In future research work, especially if the Multiple Time-step Optimization method is used to model the BRID's reservoir management, the optimal refill and drawdown schedule as well as the optimal ideal curves and relaxation zone curve could be assessed with more accuracy and certainty.

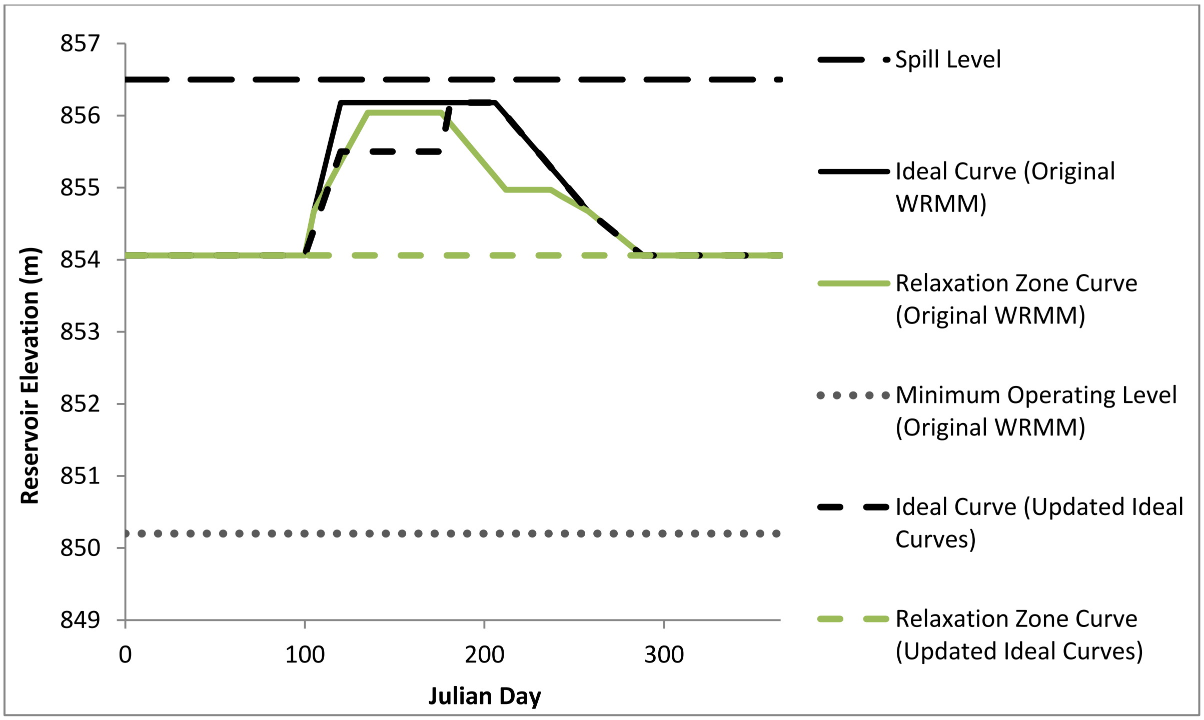


Figure 23: Travers-Little Bow Operating Curves in the Original WRMM and Updated Ideal Curves WRMM

The ideal curve and relaxation zone curve simulated for the Updated Ideal Curves scenario are the same as the ones simulated for the Current Management scenario in the case of Travers-Little Bow reservoir. Moreover, because the relaxation zone curve of Travers-Little Bow reservoir in the initial WRMM setting is above the ideal curve simulated in the Updated Ideal Curves scenario, the curve was lowered for the alternative WRMM version. As shown by Figure 23, the relaxation zone curve was maintained at the ideal winter level throughout the year. Again, it is possible that the relaxation zone level affects the optimality of the results, but the impact was considered lower than the possible benefits of assessing more realistic ideal curves and reservoir management alternatives. Finally, the refill schedule of this reservoir was kept the same for all the WRMM versions.

As shown below by Figure 24 to Figure 26, Badger, Scope and Lost Lake do not have relaxation zone curves. Their operation is guided by a zone above the ideal curve (flood control zone) and below the ideal curve (1st relaxation zone) as well as a zone below the minimum operating level (2nd relaxation zone). The changes in operating levels are indicated for the different WRMM versions developed. Similarly as indicated before, the refill schedule of these reservoirs was kept the same for all the WRMM versions.

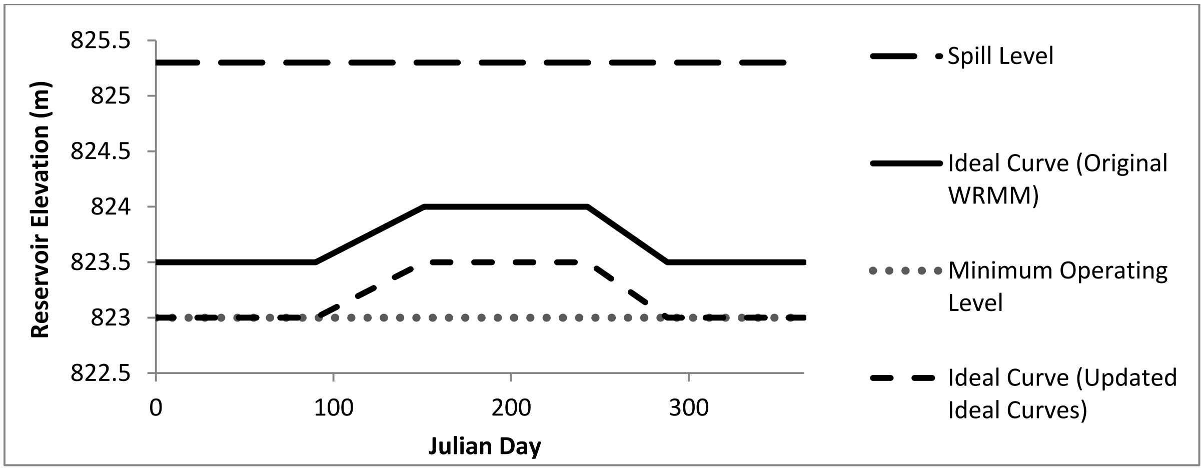


Figure 24: Badger Operating Curves in the Original WRMM and Updated Ideal Curves WRMM

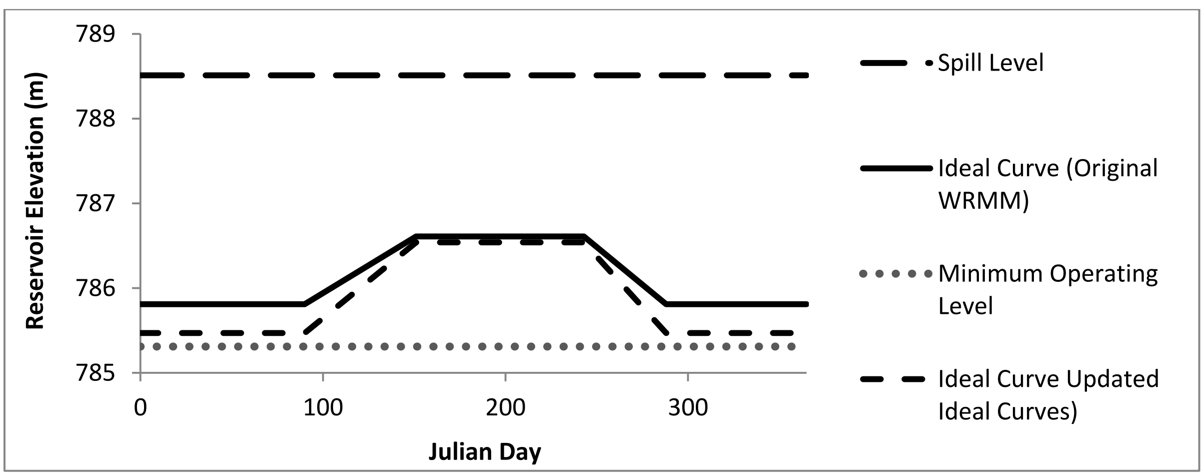


Figure 25: Scope Operating Curves in the Original WRMM and Updated Ideal Curves WRMM

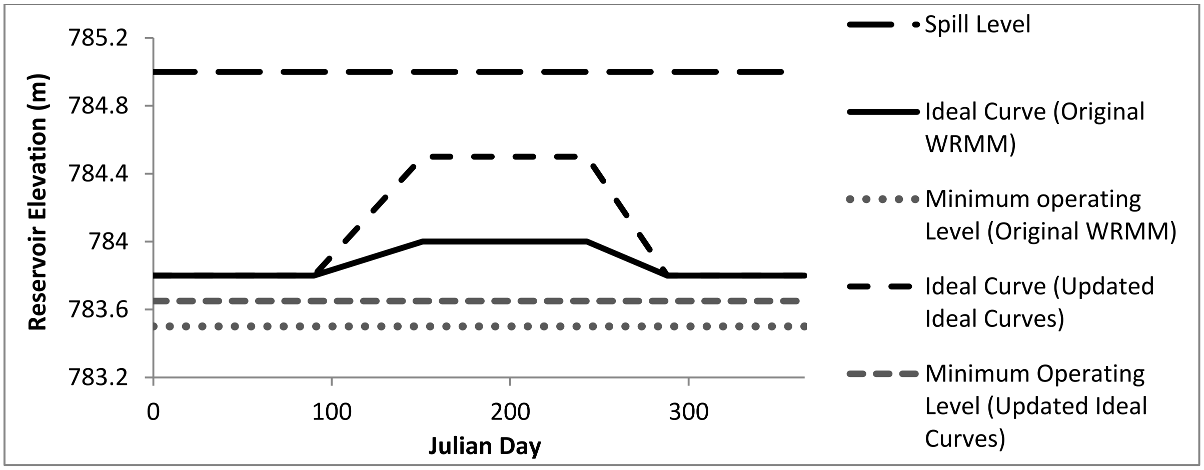


Figure 26: Lost Lake Operating Curves in the Original WRMM and Updated Ideal Curves WRMM

5.1.1.4 WRMM Modifications to Simulate Diverse BRID Reservoir Penalties

The penalties associated with each river basin component influence directly how the model will allocate the water among the different water users as well as the physical and natural components of the river basin system. Under linear programming theory, the WRMM model will minimise the total penalty cost of a simulation by allocating the water supply available at each time-step from the highest to the lowest penalty components while maintaining the water balance of the system and other physical constraints.

The current penalty scheme defining the priority of the different operating zones of the BRID's reservoirs in the original WRMM is set in a way that internal storage will be filled first (Badger, Scope and Lost Lake). As soon as the internal storage is filled, the extra water will fill Travers-Little Bow reservoir, and then McGregor reservoir. This practice ensures that if there is any shortage or cut off in the system, all users in the downstream end meet their requirements (Reza Ghanbarpour, personal communication, AEP, February 2014).

On the other hand, as reported in Chapter 3, the literature suggests an inverse set of penalties to the ones defined in the WRMM. Indeed, Lund and Guzman (1999) indicated that in the case of reservoirs in series operated to meet water supply requirements, it is preferable to fill the upper reservoir first (upstream) and empty the lower reservoir first (downstream). Their work is based on USACE (1996) previous studies. This set of rules could be implemented in the WRMM by associating lower penalties to the downstream reservoirs in order to ensure that the model will prioritize refilling of the upstream reservoirs when extra water is available and draw down the downstream reservoirs first when there are water shortages. In the case of the BRID's reservoir system, McGregor and Travers are in series on the same off-stream canal, with inflows coming in Travers-Little Bow reservoir from the Little Bow River. They form a series of three reservoirs with Badger on the north side of the district and another series of three reservoirs with Scope on the east side.

Based on these observations, it was of interest to generate a few exploratory scenarios using the various WRMM versions already developed. A total of two additional scenarios were then generated by inversing the original penalty set for the BRID's reservoirs in the SCF files:

1. The Inverse Penalties scenario represents the original WRMM setting in terms of reservoir operating zones but the penalties associated with each reservoir zone are inverted to allocate the highest penalty to McGregor (upstream) and the smallest to BRID internal storage (downstream);
2. The Current Management – Penalties scenario represents an updated version of the WRMM in which BRID's reservoir ideal curves and McGregor minimum operating level were modified to represent the district current operations and McGregor total available supply combined with an inverted set of penalties.

The first scenario aims to isolate the single effect of inverting the penalties on the simulation results. The additional scenario was developed in order to evaluate the impact of changing the penalties when the ideal curves and reservoir live storage is more representative of the BRID current management.

Table 8 presents the original penalty settings from the WRMM and the inverted penalties simulated for the exploratory scenarios. The penalties are changed in order to allocate the highest priority to McGregor and the lowest to Badger and Scope but should still ensure that the lowest operating zones have higher penalties compared to the zones closest to the ideal curve. Therefore, it was not possible to strictly conserve all the original penalty values while inverting them from one reservoir zone to another; however, the relative penalty value of each reservoir zone was inverted to simulate an inverse refill and drawdown priority of the BRID's reservoirs system. The penalties of Lost Lake operating zone were not changed as this reservoir is located in parallel with Scope Reservoir and it is not used for irrigation purposes. Moreover, the penalties associated with the zones above the ideal curve (spill zone and flood control zone) were not changed either. The minimum operating zone of each reservoir was adjusted to a high penalty value (10,000) as they represent the dead storage and therefore, the model should never use the water below this level. The inverse set of penalties developed for the Updated Ideal Curves and Current Management WRMM versions are not shown below, but the same principle was applied.

Moreover, the block 339 penalty was adjusted to be slightly below the penalty of McGregor 2nd relaxation zone to ensure that the model will not supply this irrigation block if it has to drawdown McGregor below the irrigation threshold for the Current Management version of the WRMM. The two additional penalties setting can be found in the Appendix B – Reservoir Operating Zone Inverse Penalties Developed for the WRMM.

Table 8: BRID's Reservoirs Penalties in the Original WRMM and in the Inverse Penalty Versions of WRMM

Original WRMM					
Reservoir	**Second Zone Above Ideal Curve**	**First Zone Above Ideal Curve**	**First Zone Below Ideal Curve**	**Second Zone Below Ideal Curve**	**Third Zone Below Ideal Curve**
McGregor	4 600	9 500	1	1 150	1 245
Travers-Little Bow	4 600	9 500	20	1 160	1 248
Badger		10 000	1 180	1 190	
Scope		10 000	1 180	1 190	
Lost Lake		10 000	1 180	10 000	
Block 339			1 240		
Inverse Penalty					
Reservoir	**Second Zone Above Ideal Curve**	**First Zone Above Ideal Curve**	**First Zone Below Ideal Curve**	**Second Zone Below Ideal Curve**	**Third Zone Below Ideal Curve**
McGregor	4 600	9 500	100	1 175	10 000
Travers-Little Bow	4 600	9 500	20	1 000	10 000
Badger		10 000	1	10 000	
Scope		10 000	1	10 000	
Lost Lake		10 000	1 180	10 000	
Block 339			1 170		

5.1.1.5 WRMM Modification to Simulate Other Alternatives for BRID's Reservoirs Operation

New rule curves were modeled in the WRMM in order to evaluate the impact of managing the BRID's external reservoirs solely for drought mitigation. The new curves do not agree with AEP's directives of maintaining a greater flood zone in Travers-Little Bow reservoir to prevent flooding of the Little Bow River or managing McGregor Reservoir lower for encouraging land development around the lake. The alternative curves developed are still based on interview data with the BRID and were determined to be physically feasible. The new simulated curves permit the quantification of benefits and trade-offs for irrigation development of managing the BRID's external reservoirs exclusively for water supply purposes rather than multi-purpose uses. Moreover, an additional exploratory scenario was developed in order to evaluate the impact of changing the penalties of the alternative curve settings. The two additional scenarios can be defined as:

1) The Drought Mitigation Curves scenario represents an alternative version of the WRMM in which the BRID's external reservoir ideal curves were elevated to serve drought mitigation purpose;
2) The Drought Mitigation Curves – Penalties scenario represents an alternative version of the WRMM for drought mitigation purpose combined with an inverse set of penalties.

Table 9 presents the ideal operating levels for winter and summer under the various WRMM versions. For the Drought Mitigation Curves scenario, the winter levels have been elevated for about 0.5 meter in the case of McGregor and almost 1 meter in the case of Travers-Little Bow. The ideal summer levels of McGregor and Travers-Little Bow for the Drought Mitigation Curves are the same as the ones defined in the Original WRMM version. It could be noted that McGregor real dead storage level (865.63 meters) was used in the Drought Mitigation Curves WRMM version.

Table 9: BRID's External Reservoirs Ideal Curve Operating Levels Comparison between Drought Mitigation Curves, Updated Curves and Original WRMM Versions

	Ideal Winter Level (m)		
Reservoir	**Drought Mitigation Curves WRMM**	**Current Management WRMM**	**Original WRMM**
McGregor	873.90	873.56	873.56
Travers-Little Bow	855.00	854.06	854.06
	Ideal Summer Level (m)		
Reservoir	**Drought Mitigation Curves WRMM**	**Current Management WRMM**	**Original WRMM**
McGregor	874.38	874.10	874.38
Travers-Little Bow	856.18	855.50 - 856.18	856.18

5.1.1.6 Bruce Lake Reservoir in the WID

The modification of the BRID's reservoir management in the WRMM permits more realistic evaluation of the water supply available under current operations and alternatives reservoir operations. This district's reservoirs experienced various operational changes since the original configuration of the WRMM and the amount of water diverted from the BRID can influence the water being available for the two other districts on the Bow River: the WID and the EID. However, the WID is the district with the least storage capacity and that experiences the most severe water shortages in times of drought even if it has the most senior licence. Therefore, it was considered useful to assess the benefits of adding Bruce Lake Reservoir to the WID in order to properly answer the third objective of the research project, which aims to evaluate the water supply availability under various irrigation development scenarios. This would refine the upper limit on the water supply available for irrigation for the best case scenario in terms of water security for the WID.

As a result, the WRMM has been modified by AEP's staff to represent in one case, the WID network without Bruce Lake reservoir and in a second case, the WID conveyance system including Bruce Lake reservoir. Figure 27 shows the schematic of the WID with Bruce Lake Reservoir located upstream of three of the WID's irrigation blocks. For the simulation representing the WID's current configuration, Bruce Lake reservoir is simply a junction node. Bruce Lake's available storage based on a minimum operating level of 935 meters and an ideal summer level of 939 meters is 45,500 dam^3. The WRMM version that included Bruce Lake is identified as Bruce Lake – Current Management scenario, because it represents the BRID's current reservoir operating levels as well. The work done by Huggard (2014) can be consulted for additional results. Indeed, Huggard's research permitted quantification of the range of water supply volumes available under various Bruce Lake sizes and various optimization methods and using irrigation demand input data representative of 2008.

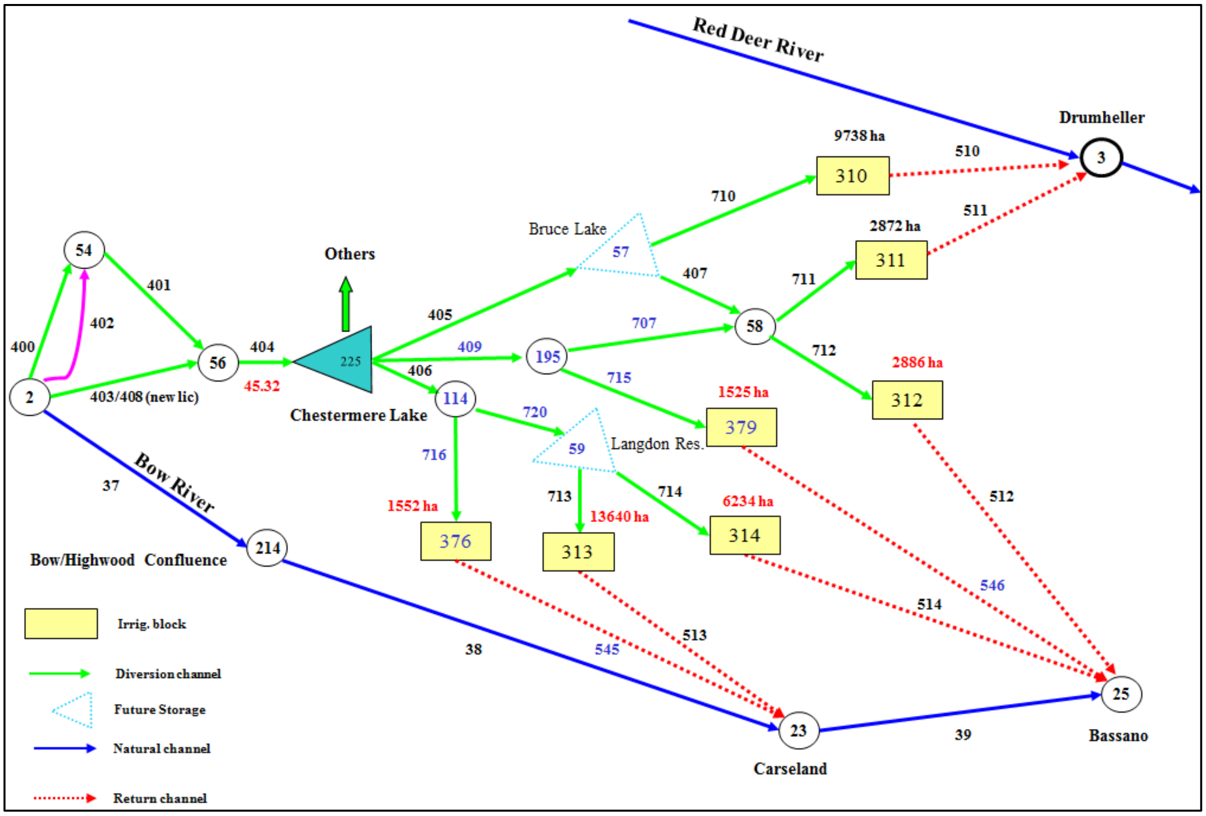
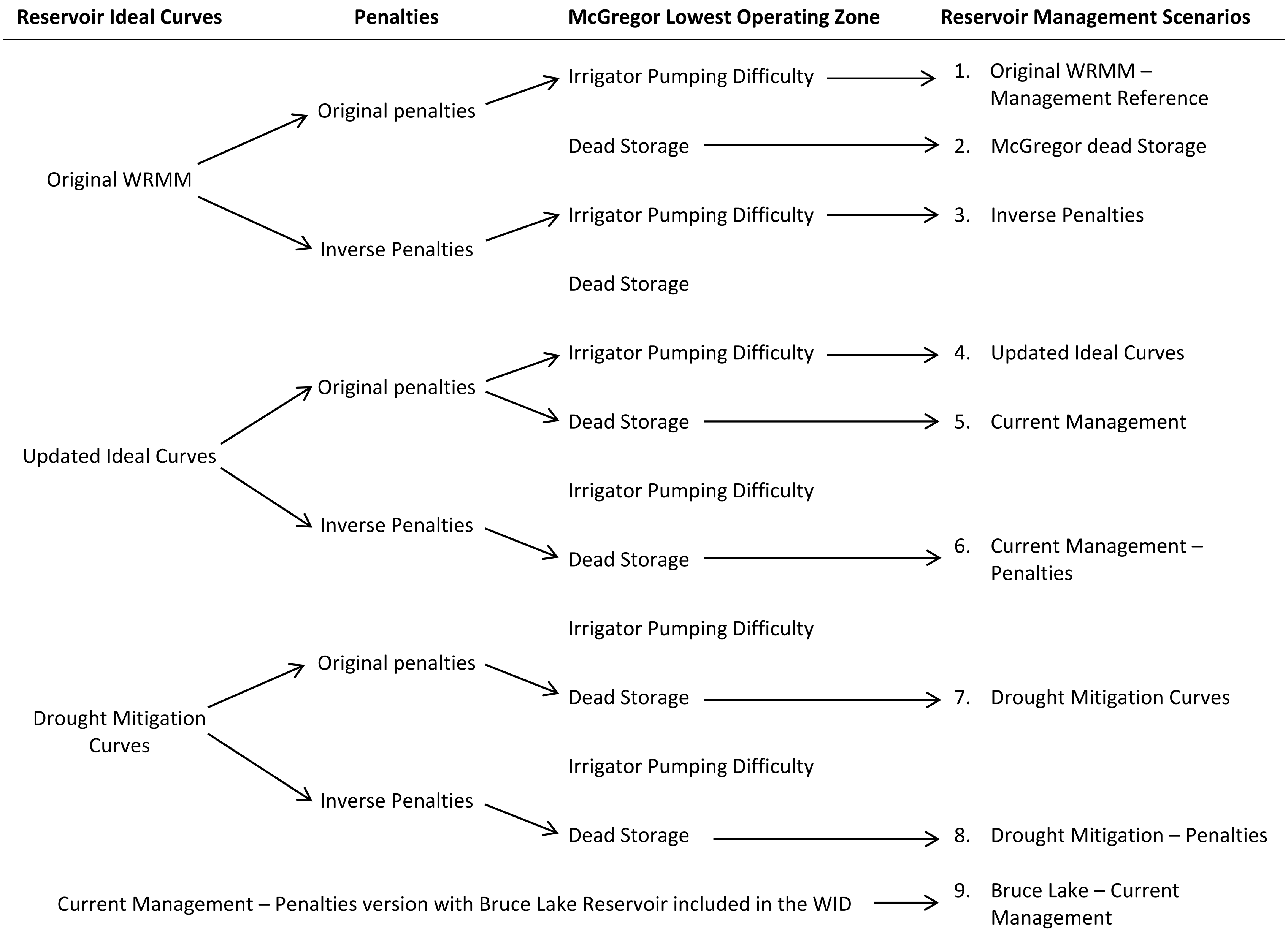


Figure 27: Western Irrigation District as Simulated in the WRMM including Bruce Lake Reservoir (Reza Ghanbarpur, AEP, personal communication, November 2014)

5.1.1.7 Reservoir Management Scenarios Diagram

The following diagram presents the various combinations of parameters changed in the WRMM to generate the BRID's reservoir management scenarios and the Bruce Lake Reservoir scenario.


Reservoir Ideal Curves
Penalties
McGregor Lowest Operating Zone
Reservoir Management Scenarios
Original WRMM
Original penalties
Inverse Penalties
Irrigator Pumping Difficulty
Dead Storage
Irrigator Pumping Difficulty
Dead Storage
1. Original WRMM – Management Reference
2. McGregor dead Storage
3. Inverse Penalties
Updated Ideal Curves
Original penalties
Inverse Penalties
Irrigator Pumping Difficulty
Dead Storage
Irrigator Pumping Difficulty
Dead Storage
4. Updated Ideal Curves
5. Current Management
6. Current Management – Penalties
Drought Mitigation Curves
Original penalties
Inverse Penalties
Irrigator Pumping Difficulty
Dead Storage
Irrigator Pumping Difficulty
Dead Storage
7. Drought Mitigation Curves
8. Drought Mitigation – Penalties
Current Management – Penalties version with Bruce Lake Reservoir included in the WID
9. Bruce Lake – Current Management

5.1.2 IDM Simulations of Water Demand for Irrigation

The impacts of expanding the land irrigated and the effect of changing crop mixes that have variable water requirements were investigated. Indeed, the irrigation districts indicated that they are reluctant to increase the risks faced by irrigators if an unreasonable expansion is reached. Moreover, changes in crop mix can affect the water supply available as some crops require greater water application over the season (Bennett *et al.* 2014), but the influence of various crop mixes on the water management has been rarely assessed in previous studies. Correspondingly, AAF's staff indicated the need for evaluating the impact of districts' expansion and more extreme crop mixes in terms of water requirements on a river basin scale level. Finally, the irrigation management practice in the field could be described as the fraction of the ideal crop water requirement that is met with a combination of rainfall and irrigation (Allan *et al.* 1998). In the IDM, the irrigation management practice is represented by the "evapotranspiration scaling factor" (K_s). AAF usually runs the IDM with an evapotranspiration scaling factor of 90% while in reality, irrigators typically supply between 60 to 100% (Bob Riewe, personal communication, AAF, October 2014). Therefore, the impact of reducing this factor to more realistic values was also examined. The methodology involved for each parameter modification and the output generated from IDM simulations are described below.

5.1.2.1 Pre-simulation steps

The IDM data originally run with the WRMM dated from 2008. For this study, these data were replaced by new data prepared by AAF representing 2012's expansion limit, crop mix and on-farm irrigation efficiency for all the southern districts: SMRID, TID, RID, MID, LID, AID, UID and MVID. These districts' demands served as input data for the Southern Tributaries sub-model of the WRMM, which was run by an AEP employee in order to update the input files serving this research's modelling work. The resulting Southern Tributaries model outputs were used as new inflows for the Main WRMM sub-model and were not changed over the course of the simulation work presented in this thesis. The IDM irrigation demands are generally conservative as AAF simulations represent the upper bound of irrigation demand for two reasons:

1. AAF uses the expansion limit of the districts as their irrigated area; however, the actual area irrigated could still be much smaller in reality;
2. The evapotranspiration scaling factor is set to 90%, which is equivalent to the upper bound of the achievable irrigation management target on a district level.

5.1.2.2 Expansion Limits Scenarios

A total of three expansion limit scenarios were simulated in the IDM: the current expansion limit, the future expansion limit and the future expansion limit considering Bruce Lake Reservoir is added to the WID's network.

The current expansion limit refers to the maximum permissible irrigated area as currently approved by each district's board. Table 10 presents the expansion limit values for the four districts simulated and indicates as well how it compares with the area currently irrigated. The difference is particularly noticeable for the WID whose expansion limit is almost the double of its currently irrigated area in 2013. The total area of the current expansion limit for all four irrigation districts combined is about 20% above the real irrigated land of 2013.

Table 10: Irrigated Area *vs* the Current Expansion Limit in 2013 (adapted from AARD 2014b)

Irrigation District	Irrigated Area (2013)	Current Expansion Limit	
	(ha)	(ha)	(% of 2013)
WID	20,150	38,446	191
BRID	87,986	105,221	120
EID	119,756	125,860	105
LNID	72,316	91,865	127
Total	300,207	361,393	120

The future expansion limit is a possible expansion that could be approved over the next 25 years (2015-2040) based on the information provided during the interviews led with the irrigation districts' managers. In the hypothesis that the WID could rely on Bruce Lake reservoir in the future, the future expansion limit approved by the WID is supposed to be greater. Therefore, the third area simulated represents the future expansion limit considering Bruce Lake reservoir, which translates in a greater expansion of the WID. Table 11 presents the three areas simulated in hectares.

Table 11: Three Expansion Limits Simulated in the IDM

Irrigation District	Current Expansion Limit	Future Expansion Limit		Future Expansion Limit - Bruce Lake	
	(ha)	(ha)	(% of current)	(ha)	(% of current)
WID	38,446	42,493	111	48,563	126
BRID	105,221	113,315	108	113,315	108
EID	125,860	129,503	103	129,503	103
LNID	91,865	91,865	100	91,865	100
Total	361,393	377,176	104	383,246	106

No additional expansion is simulated for the LNID as this district is limited by its conveyance system capacity and does not project development of irrigation above its actual expansion limit. The WID plans to expand from its actual expansion limit by approximately 11% and by as much as 26% if Bruce Lake Reservoir is added to its network. As the WID has already the greatest difference between its current expansion limit compared to its irrigated area in 2013 (see Table 10), its simulated demand is considered to be extremely conservative.

The proposed expansion limits were simulated using the IDM Scenario Builder program. In the IDM, the irrigation districts' total area is divided into a number of blocks, which represent organization units of an irrigation system. The blocks share common attributes such as weather and soil characteristics but have different areas. The future expansion limit and the proposed expansion limit considering Bruce Lake were supposed to occur proportionally in each block of a given district; if a district's expansion limit increases by 10% for example, each of this district's blocks area will increase by 10% as well. This method is a simplification of reality as the irrigation expansion normally depends on the land suitability for agriculture and the district conveyance system capacity, which could vary from one side of a district area to another. It is nevertheless the method usually employed by AAF staff and it is considered a reasonable simplification. Figure 28 shows how block size could be adjusted in the IDM Scenario Builder program.

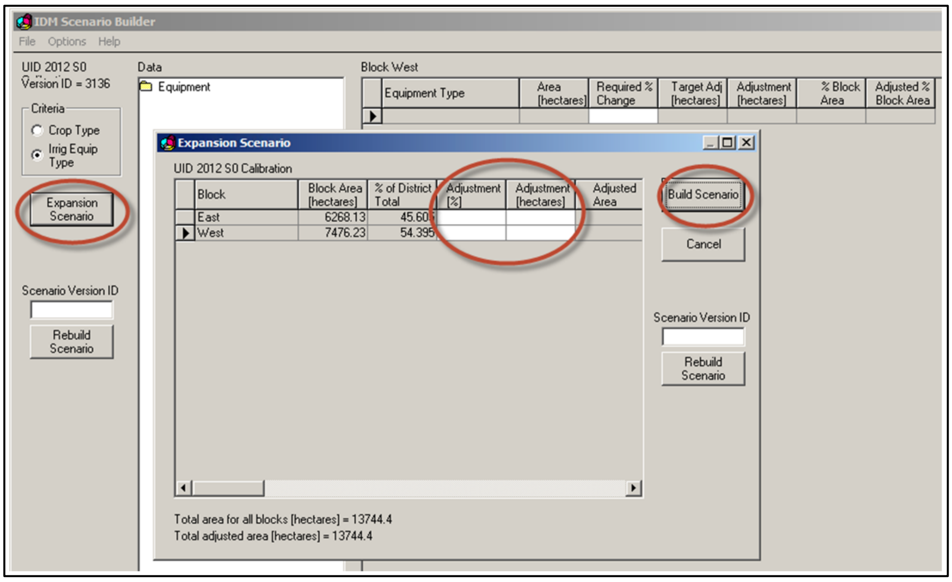


Figure 28: Adjusting the Irrigation Districts' Blocks size using the Expansion Scenario Function of the IDM Scenario Builder (Adapted from AARD 2014c)

5.1.2.3 Crop Mix Scenarios

The historical 2012 crop mix already simulated by AAF staff corresponds to the reference crop mix as it is representative of the crops currently grown in each district. The IDM Scenario Builder program was then used to generate two additional crop mixes per district; a crop mix of higher water requirements and another one of lower water requirements. The two crop mixes were defined based on criteria developed through meeting with the Alberta Land Institute-funded research group at the University of Alberta and with AAF irrigation modelling specialist staff. The aim for developing these two additional crop mixes was to generate extreme-high and extreme-low water-use crop-mixes compared to the reference case, but not necessarily representative of future crop trends within the districts. The main steps involved to define the two additional crop mixes were as follows:

- Among the crops grown in a district, one or two crops are selected to represent higher water-use crops and one or two other crops are selected to represent lower water-use crops. Totally different crops could have a similar water demand over the irrigation season, which means that the selection of one or two representative crops for the high and low water-use scenarios can encompass a larger number of crops.
- An area of approximately 25% of the total district area could be allocated to the representative high or low water-use crops chosen for each crop mix scenario. The attribution of 25% of the total area for a single crop represents the upper bound of high and low water-use scenarios, because some crops require a four-year rotation for soil quality and pest mitigation.
- When re-allocating the area to the representative high or low water-use crops chosen, the crop being replaced should be a low water-use crop when it is replaced by the representative high water-use crop and a high water-use crop when replaced by the representative low water-use crop to increase the variation in water demands between the two new crop mixes generated and the reference case.

As a comparison, the Irrigation Water Management Study Committee (2002a) also evaluated the impact of variable crop mixes for their study. They considered an increased area of forages, oil seeds and speciality crop and a decreased area allocated for cereal grains. Their method consisted of using an area adjustment factor varying from 1 (no change) to 3 (three times more land is allocated to a particular crop). Their projections were based on economic factors rather than water-use considerations as is the case in this thesis. The crop mixes developed for this research represent more extreme changes, which should encompass the lowest to highest possible water demands based on crop mix changes.

To simulate crop water requirements, the IDM calculates the crop-specific evapotranspiration (ET_a in mm/day) under adjusted conditions as defined by the equation (6) (Allen *et al.* 1998):

$$ET_a = ET_0 \times K_c \times K_S \tag{6}$$

where ET_0 is defined as the evapotranspiration rate (mm/day) of a grass reference crop, not short of water, which permits accounting for the various weather conditions and is ideally computed using the Penman-Monteith method of Allen *et al.* (1998). In the IDM, however, the ET_0 is estimated directly from the weather data or with Jensen-Haise, Modified Penman or Priestley-Taylor equations (IWMSC 2002b). The K_c value is a dimensionless parameter, which refers to all the specific crop characteristics affecting its evapotranspiration rate such as the type of crop or the growing stage. The K_S represents the evapotranspiration scaling factor presented before, which is a percentage of the evapotranspiration that is satisfied by a combination of rainfall and irrigation due to management practices in the field (Allen *et al.* 1998).

A total of fifty crops commonly grown in southern Alberta can be represented in the IDM and are defined by the following data:

- Crop type (forage, cereal, oil seed or speciality crop);
- Minimum and maximum root depths (mm);
- Seeding, cover, harvest and cut dates given relative to the wheat planting date (Julian day);
- Irrigation threshold (%), which is the soil moisture relative to the maximum soil moisture that will prompt an irrigation application (usually set with a randomization function);
- Random seeding range (Julian day), which is defined as the number of days before or after the normal planting date that the crop will be planted (usually set with a randomization function at each simulation);
- Crop coefficient curve (dimensionless), which consists of the daily evapotranspiration coefficient (K_c) for Julian days 105 to 288.

Figure 29 gives an example of three crop coefficient curves for crops represented in the IDM, which have low water requirements and Figure 30 shows the crop coefficient curves of three crops having high water requirements. The two figures present similar maximum and minimum K_c values but in the case of the sugar beets, alfalfa two-cut or grass seed, the K_c values are above zero both sooner and later in the season compared to the canola, fresh peas and barley crops. As a result, the crops presented in Figure 30 have a higher evapotranspiration rate for an extended period of time, which needs to be compensated by more irrigation water.

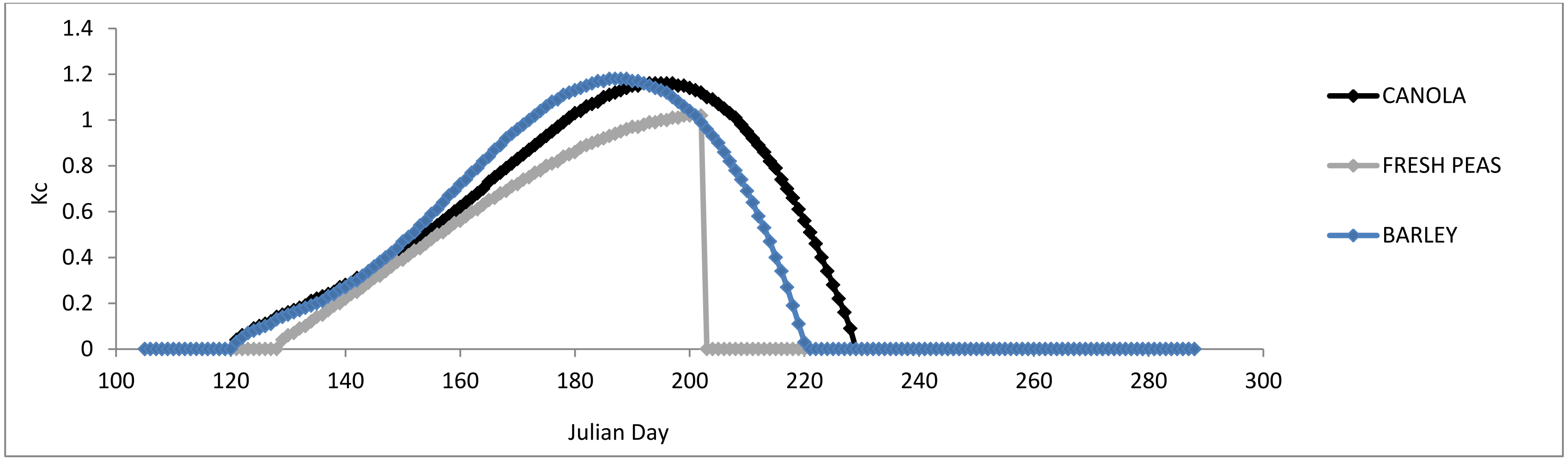


Figure 29: Crop Evapotranspiration Curve of the Daily Evapotranspiration Coefficient (K_c) from IDM for 3 Low Water-use Crops; Canola, Fresh peas and Barley

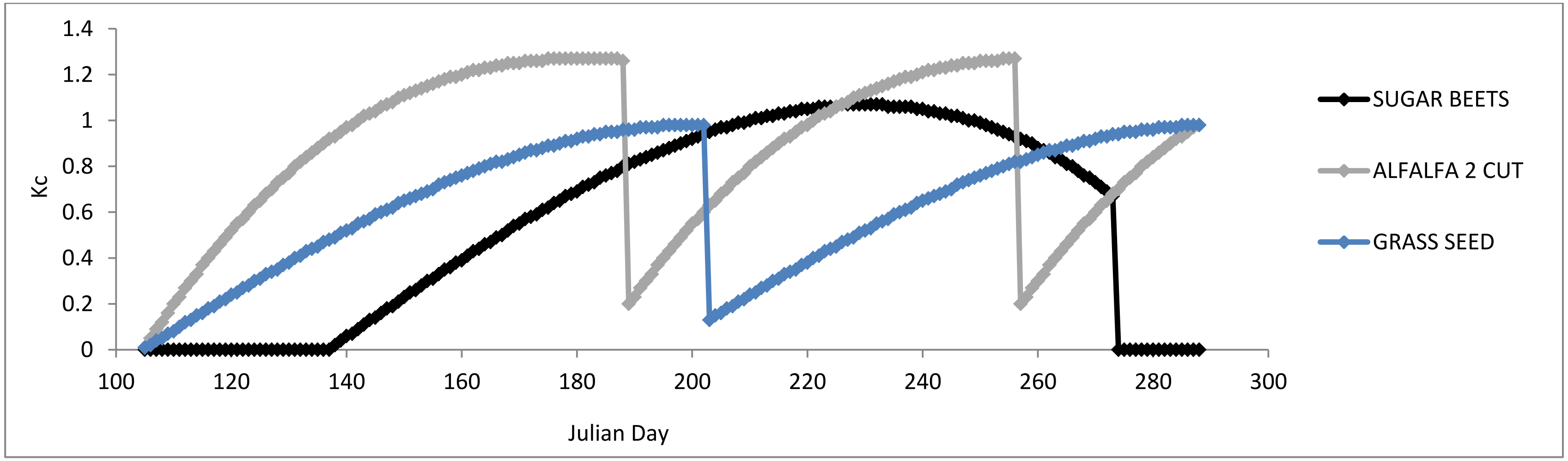


Figure 30: Crop Evapotranspiration Curve of the Daily Evapotranspiration Coefficient (K_c) from IDM for 3 High Water-use Crops; Sugar beets, Alfalfa 2 cut and Grass seed

To compare the seasonal crop water requirements from one crop to another, the daily K_c values from Julian day 105 to 288 were aggregated into one dimensionless value called the cumulative crop evapotranspiration coefficient (cumulative K_c). The cumulative K_c values are presented in Table 12 and are ordered from the highest (higher seasonal evapotranspiration) to the smallest (lower seasonal evapotranspiration) and by crop type (cereals, forages, oil seeds and speciality crops). As shown by Table 12, on average, cereals and oil seeds require less water than forages or speciality crops, but some forages and speciality crops have very low water requirements as well.

Table 12: Cumulative Evapotranspiration Coefficient (K_c) from IDM Ordered by Crop Type for the Major Crops Simulated

Crop type	Crop	Cumulative Kc	Crop type	Crop	Cumulative Kc
CEREALS	GRAIN CORN	87.6	OIL SEEDS	SAFFLOWER	91.9
	CPS WHEAT	79.9		FLAX	77.4
	TRITICALE	79.9		CANOLA	72.0
	WINTER WHEAT	79.9		MUSTARD	71.8
	BARLEY	79.1	SPECIALTY	GRASS SEED	117.5
	DURUM WHEAT	79.1		SUNFLOWER	109.0
	HARD SPRING WHEAT	79.1		ALFALFA SEED	109.0
	RYE	79.1		SEED POTATOES	103.4
	SOFT WHEAT	79.1		SUGAR BEETS	103.2
	OATS	73.8		POTATO	96.2
FORAGES	ALFALFA 2 CUT	160.5		FABA BEANS	95.8
	ALFALFA HAY	160.5		NURSERY	79.9
	ALFALFA 3 CUT	143.6		DILL	79.1
	ALFALFA SILAGE	143.6		LENTILS	78.4
	BARLEY SILAGE UNDERSEED	119.1		FRESH CORN	69.1
	NATIVE PASTURE	117.6		DRY PEAS	67.7
	BROME HAY	114.2		MARKET GARDENS	67.1
	TIMOTHY HAY	106.1		MINT	64.1
	GRASS HAY	104.7		DRY BEANS	63.7
	MILK VETCH	96.2		CARROTS	60.7
	CORN SILAGE	87.6		FRESH PEAS	45.4
	TAME PASTURE	78.8			
	BARLEY SILAGE	69.5			
	OATS SILAGE	66.2			
	GREEN FEED	56.8			

Using the Scenario Builder program, it was possible to modify an existing crop mix scenario to generate a new one, but it was not possible to develop a totally new crop mix from nothing.

Therefore, the cumulative K_c values presented above were used to compare the crops grown in the 2012's crop mix simulated in the IDM by AAF from which the high and low water-use crop mix scenarios were generated for each district.

Each block dividing an irrigation district's area in the IDM comprises a number of field units representing a smaller area where the same crop and irrigation method is used. When selecting the Crop Type criteria in the Scenario Builder, the block data are detailed as shown by Figure 31. By clicking on a given crop folder, the list of the field units and their respective area is listed as illustrated by Figure 31 as well. In order to create a high water-use crop mix, the following procedure was executed for each irrigation district:

1. Open the first block of the irrigation district;
2. Find the highest water-use crop grown in the block based on the cumulative K_c value as indicated in Table 12;
3. Allocate 25% of the block total area to the crop chosen in 2) by transferring a number of fields where low water-use crops are grown starting from the lowest water-use crop;
4. When transferring fields from a low water-use crop to the highest water-use crop chosen in 2), only transfer a number of fields representing about 50% of the total area originally allocated to the crop being replaced;
5. If the highest water-use crop is already grown over 25% or more of the block area, pass to another block without changing the crop mix;
6. When all the blocks have been assessed, the district crop mix has been changed.

For the low water-use crop mix, the same procedure was applied but the lowest water-use crop was used for the step 2) and the high water-use crops were used for the step 3).

The resulting crop mixes, 2012's crop mix, high water-use crop mix and low water-use crop mix, are presented in Figure 32 for the four districts simulated in the main WRRM sub-model. In order to minimize the number of variables presented in the figure, the different crops were organized by crop type (forage, speciality crops, cereal, and oil seeds) and by water-use (very high, high, and low water-use). The average seasonal water demand for some of the crops is also indicated in the legend in order to depict the water-use variation among the different crops categories. In brief, the low water-use crops approximately require around 400 mm of water per season whereas the high water-use requires more than 500 mm to almost 700 mm in the case of alfalfa forages. The values are based on AAF data from 80% probability level of agro-climatic conditions (AARD 2012). The detailed list of the crops grown in each district and their respective area for the three crop mixes simulated can be found in the Appendix C – Additional IDM Simulation Data.

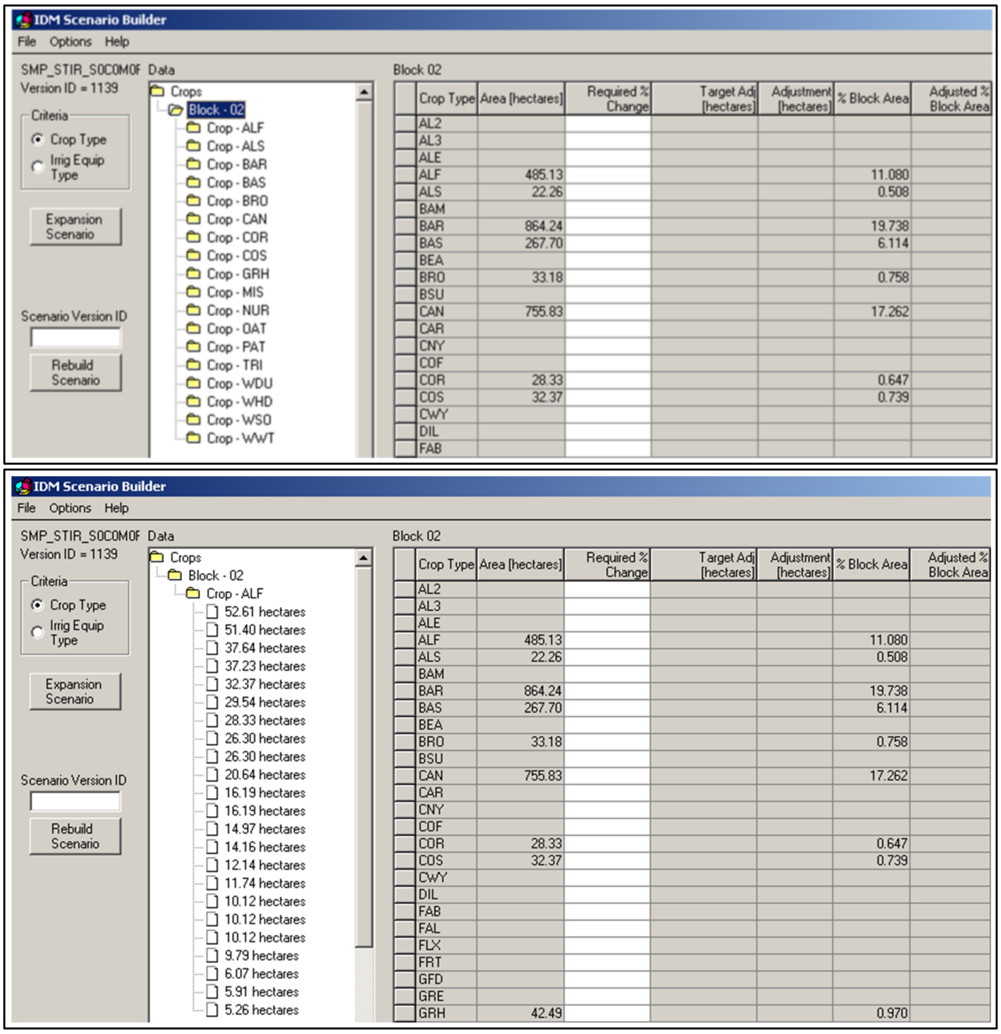


Figure 31: Crops and Fields by Block in the IDM Scenario Builder (Adapted from AARD 2014c)

Legend for Figure 32

(black)	Forage - Very High Water-Use: Alfalfa Hay, Alfalfa 2 cuts, Alfalfa 3 cuts, Alfalfa Silage (680 mm)
(dark grey)	Forage - High Water-Use: Corn Silage, Native Pasture, Brome Hay, Grass Hay … (400 mm)
(green)	Forage – Low Water-Use: Barley Silage, Oat Silage, Green Feed … (370 mm)
(white)	Speciality Crops- High Water-Use: Grass Seeds, Alfalfa Seeds, Potatoes, Sugar Beets … (510 – 560 mm)
(dark grey)	Speciality Crops - Low Water-Use: Peas, Beans, Canola Seeds, Vegetables ... (380-400 mm)
(light grey)	Cereal - Low Water-Use: Wheat, Barley, Rye … (390-480 mm)
(light blue)	Oil Seeds - Low Water-Use: Canola, Flax, Mustard, Safflower (410-480 mm)

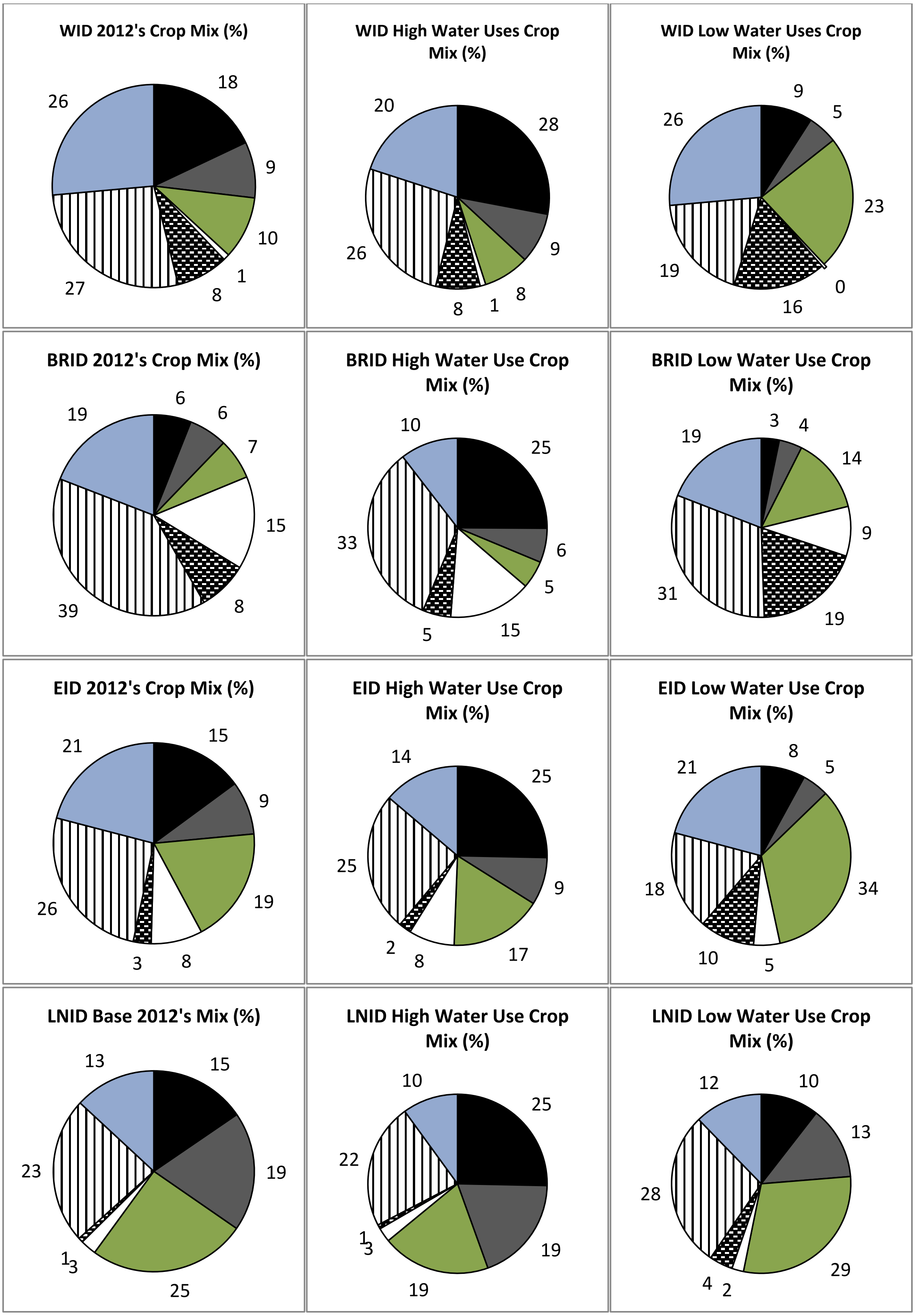


Figure 32: Crop Mixes Simulated in the IDM

5.1.2.4 Evapotranspiration Scaling Factor

In order to explore scenarios representing the lower bound of irrigation demands, the original evapotranspiration scaling factor value of 90% was reduced to more realistic values for each district varying from 60% to 80%. The new evapotranspiration scaling factors were determined based on the ratio between the current irrigation districts' average water application reported during the interviews and the average irrigation demands from IDM's simulations representative of the current irrigations districts development level. Indeed, the IDM's reference scenario is based on the current irrigation district's expansion limit, 2012's crop mix as well as the 2012's on-farm and distribution system efficiency combined with an evapotranspiration scaling factor of 90%. More specifically, the alternative evapotranspiration scaling factors associated to each district are 75% for the WID, 80% for the BRID, 70% for the EID and 60% for LNID.

5.1.2.5 Irrigation Demands Simulated

The combination of the three parameters modified in the IDM model, the expansion limits, crop mixes and evapotranspiration scaling factors, led to multiple levels of water-use. The matrix presented in Table 13 summarizes the 18 irrigation demand scenarios simulated.

The IDM's simulations take into account the variability of the irrigation demand from year to year induced by inconsistent rainfall, temperature and other meteorological factors. Indeed, the IDM produces ideal weekly irrigation demands based on the historical meteorological conditions represented at a township scale (six-by-six mile squares) (Andrea González, personal communication, AAF, December 2014) for a series of years starting from 1928 to 2012 for this thesis.

Table 13: Matrix of IDM's Scenarios

	Current Expansion Limit	Future Expansion Limit	Future Expansion Limit – Bruce Lake	Evapotranspiration Scaling Factor (K_s)
2012's Crop Mix	Reference Water-use	Expansion – Actual Water-use	Bruce Lake Expansion –Actual Water-use	**90%**
High Water-use Crop Mix	No Expansion – High Water-use	Expansion – High Water-use	Bruce Lake Expansion – High Water-use	**90%**
Low Water-use Crop Mix	No Expansion – Low Water-use	Expansion – Low Water-use	Bruce Lake Expansion – Low Water-use	**90%**
2012's Crop Mix	Current Water-use – Low Target*	Expansion – Actual Water-use – Low Target	Bruce Lake Expansion –Actual Water-use – Low Target	**<90%**
High Water-use Crop Mix	High Water-use – Low Target	Expansion – High Water-use – Low Target	Bruce Lake Expansion –High Water-use – Low Target	**<90%**
Low Water-use Crop Mix	Low Water-use – Low Target	Expansion – Low Water-use – Low Target	Bruce Lake Expansion –Low Water-use – Low Target	**<90%**

***The Current Water-use – Low Target scenario was not simulated, because the IDM's reference files representative of the current expansion limit and 2012's crop mix were only available under the usual K_s factor of 90%**

The output files of the IDM's simulations were used as input files for the irrigation blocks of the four irrigation districts simulated in the Main WRMM sub-model: the WID, BRID, EID and LNID. However, as the blocks used in IDM's simulation are not exactly the same as the irrigation blocks represented in the WRMM, the IDM block outputs are aggregated together to match the WRMM block boundaries (IWMSC 2002b). Indeed, the IDM's blocks represent with more accuracy the physical irrigation network of a district while the WRMM irrigation blocks are an over-simplification of a larger irrigated area and comprise one single inlet and outlet to facilitate water allocations simulation. Moreover, because the WRMM is run only for a series of historical hydrological and meteorological data starting from 1928 to 2001 (74 years), the irrigation demand data from the IDM simulation have to be reduced to 74 years as well. This historical time-series permits simulation of the historical variations in water demand and water supply caused by the environmental factors (river flows, rainfall, temperature, etc.), but all the other factors affecting water demands (irrigation system efficiency, crop mix, evapotranspiration scaling factor, etc.) are constant over the length of the 74 years simulation and correspond to the different parameter settings defined for each irrigation demand scenario. The methodology used to change the ideal irrigation demand input in the WRMM from the IDM's simulations is detailed in the Appendix E – Step by Step Method for Generating WRMM Scenarios based on New IDM's Files.

In order to analyse the irrigation demands generated by each water-use scenario, the WRMM model was run to produce a time-series of weekly ideal irrigation demands representative of the historical meteorological conditions for the study period of 1928 to 2001. In the WRMM, the irrigation demands are given as weekly irrigation depth (in mm) for each irrigation blocks and for each year simulated. To calculate the irrigation demand by district, the following procedure is followed:

1. Sum all weekly irrigation demands to obtain the annual irrigation demand (in mm) for each irrigation blocks;
2. Average all annual irrigation demands for all years simulated (74 years) to obtain the average annual irrigation demand (in mm) for each irrigation block;
3. Sum all average annual irrigation demands of each irrigation district's block using the area-weighted factors (see Appendix D – Irrigation Districts' Blocks Area-weighted Factors).

The simulated ideal irrigation demands represent the sum of the water taken from the canal network by the on-farm irrigation systems, which comprises the net on-farm irrigation application, the irrigation losses and the return flows as well as the down-time losses (water unused because of irrigation systems' down-time for open canal systems). Note that by averaging all the yearly irrigation demands, the specific high demand values for hot, dry years are not depicted. The average irrigation demand values still provide a general assessment of the relative irrigation demand level of each scenario simulated, whereas the more specific comparison of dry, normal and wet year results is done in the result and discussion analysis. The average irrigation demands simulated for each irrigation district are presented in Figure 33 to Figure 36. Moreover, the irrigation demands' variability induced by the historical rainfall, temperature and other meteorological factors is also included in the figures through error bars representing the standard deviation of the data time-series. The standard deviation for the scenarios simulated varied from 58 to 84 mm. The maximum annual irrigation demand simulated from the series of 74 years is indicated for each scenario. Finally, the current average irrigation demand and the maximum allowed irrigation depth in time of drought reported by each irrigation district during the interviews are indicated as a comparison.

To minimize the variables presented in the Figure 33 to Figure 36, the irrigation demands were averaged for the scenarios that had the same crop mix (reference, low or high water-use crop mixes) and the same evapotranspiration scaling factor (90% or a smaller value varying from 60 to 80%) but only represented different expansion limits. The irrigation demands per unit area should be identical if the only parameter that is changed is the total area irrigated. However, the irrigation demand depth could vary slightly between two scenarios as a consequence of randomizing function used for two parameters of the IDM: 1) the random seeding date indicates various seeding dates within a pre-defined normal planting range of days for each crop grown and 2) the random irrigation threshold defines a variable ratio of current soil moisture to maximum soil moisture that initiates irrigation. These random parameters allow more realism for the simulation results as the seeding date and irrigation schedule will vary from one field to another, but produce slightly different results. More particularly, except for WID, the irrigation districts have irrigation demands that could vary up to 2 mm from one expansion limit scenario to another. As a comparison, WID average ideal irrigation demands could change to as much as 20 mm.

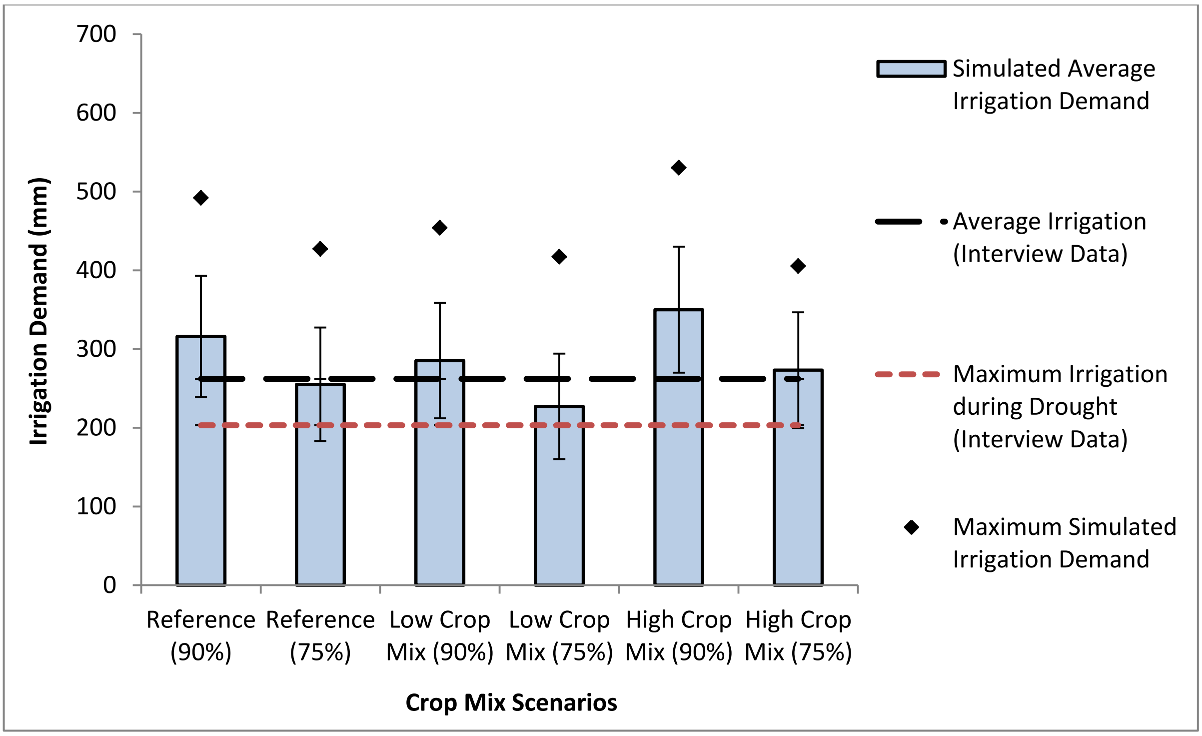


Figure 33: Simulated Average Irrigation Demands for WID (1928-2001)

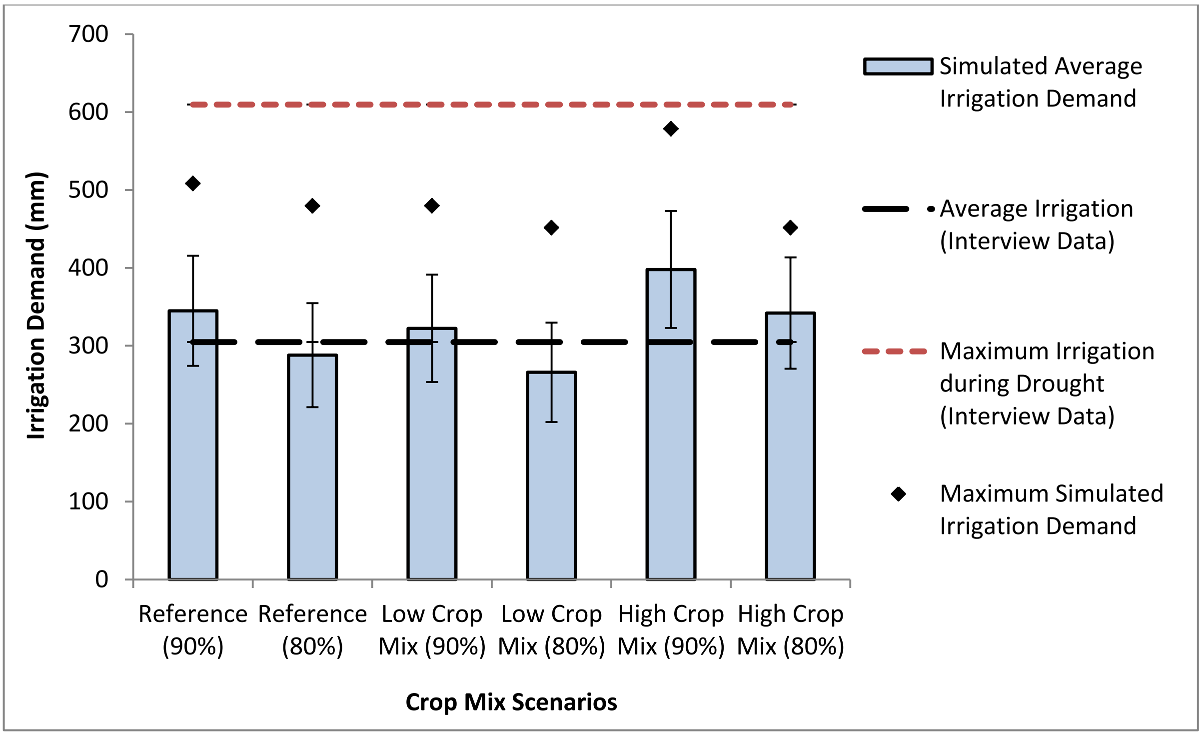


Figure 34: Simulated Average Irrigation Demands for BRID (1928-2001)

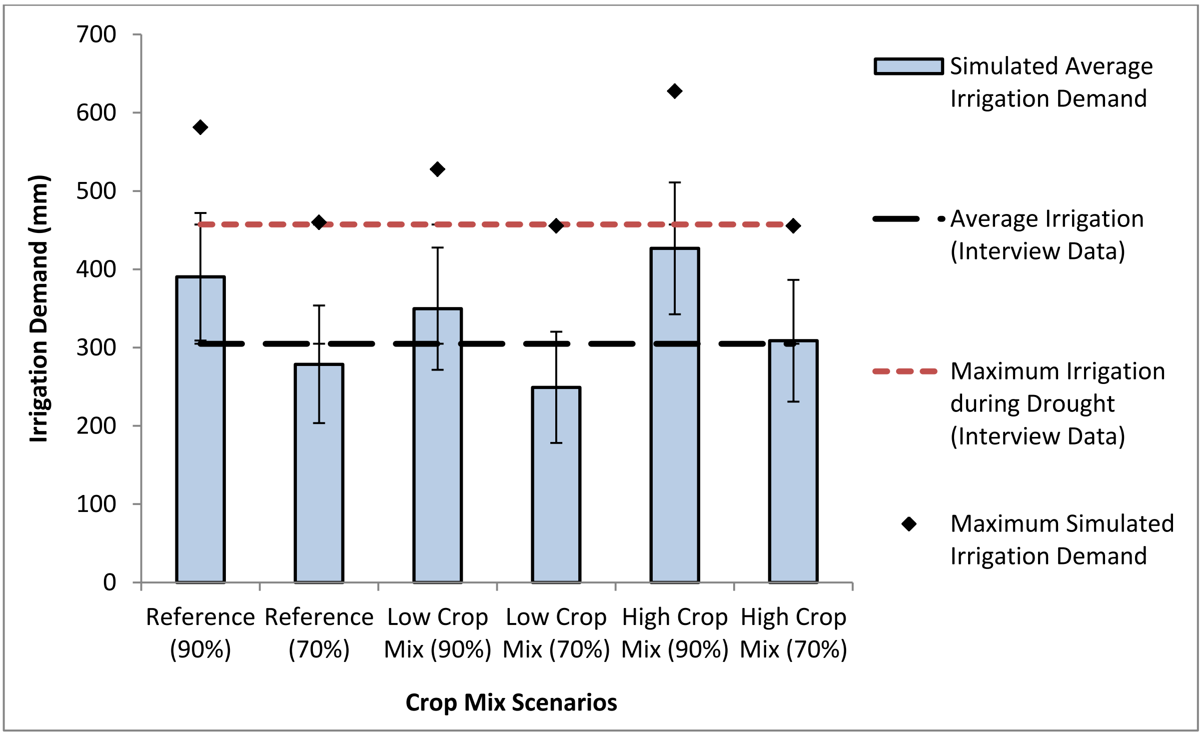


Figure 35: Simulated Average Irrigation Demands for EID (1928-2001)

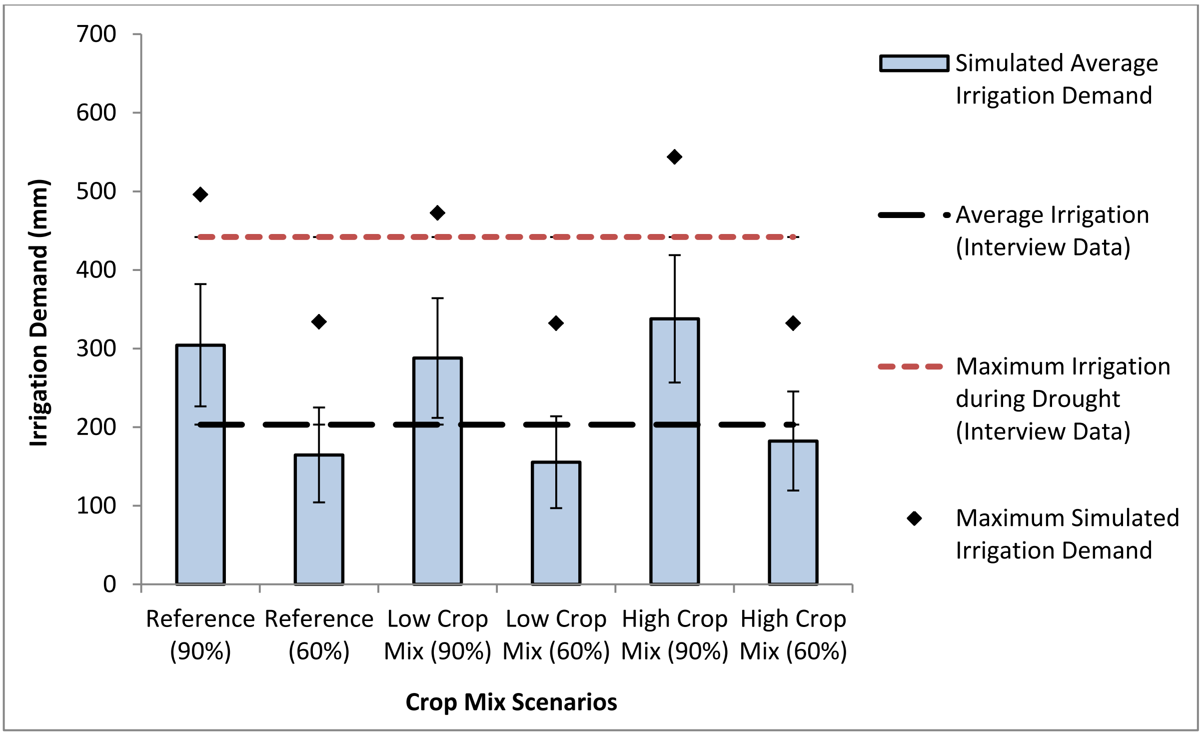


Figure 36: Simulated Average Irrigation Demands for LNID (1928-2001)

As shown by the figures above, the reference scenarios representing the 2012 crop mix, but using a smaller K_s value, led to modelling results closer to the average irrigation reported by the irrigation districts' interview data. However, lowering the K_s still underestimates the average irrigation demands, from as low as about 5 mm (WID) to about 35 mm (LNID). In comparison, using an evapotranspiration scaling factor of 90% overestimates the average irrigation demands by about 40 mm (BRID) to as much as 100 mm (LNID). The overestimation of the current water-use by the WRMM has also been reported in the past by Sheer *et al.* (2013). However, when assessing the risks for irrigation under different states of agricultural development, it would be safer to overestimate the irrigation demands rather than underestimate them. Nevertheless, it is important to consider how conservative the simulation results are in terms of water-use.

Moreover, except for the case of the BRID, all districts apply an irrigation limit in times of drought that is below or close to the maximum simulated demand for several or all of their water-use scenarios. This means that according to the IDM's simulations, irrigators from the WID, EID and LNID should be affected to some extent by irrigation restrictions imposed by their district in time of drought even under variable crop mixes. However, the EID and LNID's maximum irrigation demands simulated under a lower evapotranspiration scaling factor remains below the irrigation limit in time of drought even if a high water-use crop mix is grown. The WID has the smallest reservoir storage capacity and thus, in time of water shortages, this district has to impose more severe restrictions on its irrigators' allocations. As shown by the simulations results, even if a lower water-use crop mix is in place and a target irrigation of about 75% is used, the irrigators' average ideal demands lie above the district limit in time of water shortages.

Changing the crop mix from the 2012 crop mix to a low water-use crop mix could decrease the average irrigation demand per unit area of about 15 mm (LNID) to as much as 40 mm (EID) for scenarios that have a K_s value of 90%. On the other hand, changing the crop mix for a high water-use crop mix could lead to an increase of about 20 mm (WID) to as much as around 50 mm (BRID) still comparing scenarios that have a K_s value of 90%.

In summary, the various water-use scenarios obtained from the IDM simulations allow the generation of minimum and maximum average irrigation demands of approximately 230 to 355 mm (WID), 265 to 400 mm (BRID), 250 to 430 millimeters (EID) and 155 to 340 millimeters (LNID) under the historic meteorological conditions of the study period. Table 14 presents the average irrigation demand values for all the scenarios assessed. The difference in irrigation demands from the Reference Water-use scenario is also indicated as a percentage of the average irrigation demand volume. The complete results are presented in the Appendix C – Additional IDM Simulation Data.

Table 14: Summary of the Area-Weighted Average Irrigation Demands Simulated for all the IDM Scenarios

	Current Expansion Limit	**Future Expansion Limit**	**Future Expansion Limit – Bruce Lake**	**Evapotranspiration Scaling Factor (K_s)**
2012's Crop Mix	348 mm 1,258,801 dam^3 (Reference)	347 mm 1,309,240 dam^3 (+4.0%)	346 mm 1,326,002 dam^3 (+5.3%)	**90%**
High Water-use Crop Mix	388 mm 1,402,354 dam^3 (+11.4%)	389 mm 1,465,831 dam^3 (+16.5%)	386 mm 1,478,184 dam^3 (+17.4%)	**90%**
Low Water-use Crop Mix	320 mm 1,157,300 dam^3 (-8.1%)	319 mm 1,202,992 dam^3 (-4.4%)	318 mm 1,217,797 dam^3 (-3.3%)	**90%**
2012's Crop Mix	Not simulated	251 mm 947,890 dam^3 (-24.7%)	251 mm 960,936 dam^3 (-28.0%)	**<90%**
High Water-use Crop Mix	284 mm 1,202,992 dam^3 (-18%)	284 mm 1,071,467 dam^3 (-14.9%)	282 mm 1,078,901 dam^3 (-14.3%)	**<90%**
Low Water-use Crop Mix	237 mm 857,051 dam^3 (-31.9%)	224 mm 846,607 dam^3 (-32.7%)	224 mm 857,222 dam^3 (-31.9%)	**<90%**

5.1.2.6 Irrigation Development Scenario Diagram

The previous section detailed the different combinations of variables, which permitted production of the various water-use scenarios. However, from the 18 runs presented in Table 13, only a few were selected to serve as irrigation demands for the analysis of the available water supply in the Bow River Basin using the WRMM model. The selection of the water-use scenarios was based on their capacity to best answer the research objectives. To assess the second research objective, which aimed to compare the impact on the Bow River Basin of various reservoir management strategies in the BRID, the following scenario was selected:

1. No Expansion – High Water-use (current expansion limit, high water-use Crop mix, K_s = 90%);

It was determined that to properly compare different reservoir management options, the irrigation demands simulated for all irrigation districts modelled in the Main WRMM sub-model should generate water scarce conditions to some extent. If the water availability is never threatened for one or more districts, it would be harder to evaluate the real benefits of one reservoir management alternative *versus* another. For example, using the 2012 crop mix or the low water-use crop mix could lead to almost no water deficits in the BRID as this district relies on large reservoir storage. However, if the irrigation demands applied to the WRMM represent extremely high water demands, the best reservoir management option selected could not be suitable under more normal water-use conditions. Therefore, the No Expansion – High Water-use scenario seemed a good compromise between too low or too high water demands.

To assess the third research objective, which aims to provide bounding water supply values available for a range of low to high irrigation levels under various hydrological and meteorological conditions, the following scenarios were used:

2. Reference Water-use (current expansion limit, 2012's crop mix, K_s = 90%);
3. Expansion – High Water-use (future expansion limit, high water-use crop mix, K_s = 90%);
4. Low Water-use – Low Target (current expansion limit, low water-use crop mix, K_s < 90%);
5. Bruce Lake Expansion – High Water-use (future expansion limit if Bruce Lake is built, high water-use crop Mix, K_s = 90%).

In order to assess how changes in water demands affect the water supply available for irrigation in the Bow River Basin, it was necessary to have scenarios representing extreme-low to extreme-high water-use as well as the reference water-use scenario. Logically the lowest bound of irrigation demand was best represented by the Low Water-use – Low Target scenario because it corresponded to the lowest irrigation requirements simulated through the IDM. Similarly, the Expansion – High water-use scenario produced the highest irrigation requirements, which was useful to simulate the highest bound of irrigation demands. The Reference Water-use scenario corresponding to the IDM input data normally used by the government agencies in their simulation work was representative of the current water demands conditions. Finally, the Bruce Lake expansion – High Water-use scenario was selected to assess how the Bow River Basin and particularly the WID could benefit from the construction of Bruce Lake Reservoir in terms of water supply availability. This would add another upper limit of the water supply available under irrigation development.

5.1.3 Performance Assessment

In order to evaluate the short- to long-term risks for the irrigation sector of different reservoir management strategies and irrigation demand scenarios, various aspects of the scenario performances were evaluated. The most critical outcome to consider is the water deficit simulated for irrigation, because if not enough water supply is available to meet the crops' water requirements, the crop yield will decrease and will reduce the financial returns for irrigators (IWMSC 2002c). Moreover, the scenario results should be analysed to determine if the province of Alberta could deliver annually to the Saskatchewan border at least 50% of the natural flow of the South Saskatchewan River under the Master Apportionment Agreement. Finally, the scenarios' capacity to minimize river diversions in summer when the river water quality is the most threatened in order to reduce the negative impact of irrigation on riparian and fish habitats could be compared. These three aspects of the performance assessment are detailed in this section.

5.1.3.1 Irrigation Deficits

Different measures of the water deficits could be used to compare the risks for irrigation from one scenario to another. IWMSC (2002c) suggests that water shortfalls could have minimal to severe consequences on crop yields according to their magnitude, frequency, duration in terms of consecutive years affected by deficits and their timing. Similarly, the widely cited study of Hashimoto *et al.* (1982) recommends evaluating the performance of time-series data by the measures of reliability, resilience and vulnerability. These measures are based on the determination of a threshold value separating the satisfactory from unsatisfactory states. In the case of characterizing water deficit risks, the reliability could be viewed as how often the deficits are under an acceptable level, the resilience as how often a year with acceptable water deficits follows a year of unacceptable deficits, and finally, the vulnerability as how much above the threshold of an acceptable deficit the unacceptable water deficits are on average.

For a time-series *T* of a number of *n* years, the water deficit values (X_t) are considered acceptable if they are equal or smaller than a total deficit threshold value (X_T). The reliability can be defined as the number of years for which the water deficits are in a satisfactory state divided by the total number of years in the time-series as shown by equation (7):

$$Reliability\ (X) = \frac{\#of\ time\ X_t \leq X_T}{n} \tag{7}$$

Resilience can be expressed as the probability that if the water deficits are unsatisfactory for a given year ($X_t > X_T$), the succeeding year will be satisfactory ($X_t \leq X_T$) as detailed by equation (8):

$$Resilience\ (X) = \frac{\#of\ times\ a\ satisfactory\ state\ follows\ an\ unsatisfactory\ state}{\#of\ times\ an\ unsatisfactory\ state\ occurs} \tag{8}$$

Finally, vulnerability is determined as the average difference between the unsatisfactory water deficits and the deficit threshold value as defined by the equation (9):

$$Vulnerability\ (X) = \frac{\sum \max\ (X_t - X_T, 0)}{\#of\ times\ an\ unsatisfactory\ state\ occurs} \tag{9}$$

Figure 37 and Figure 38 present graphically the reliability and resilience of a series of annual water deficits using a threshold value of 100 mm.

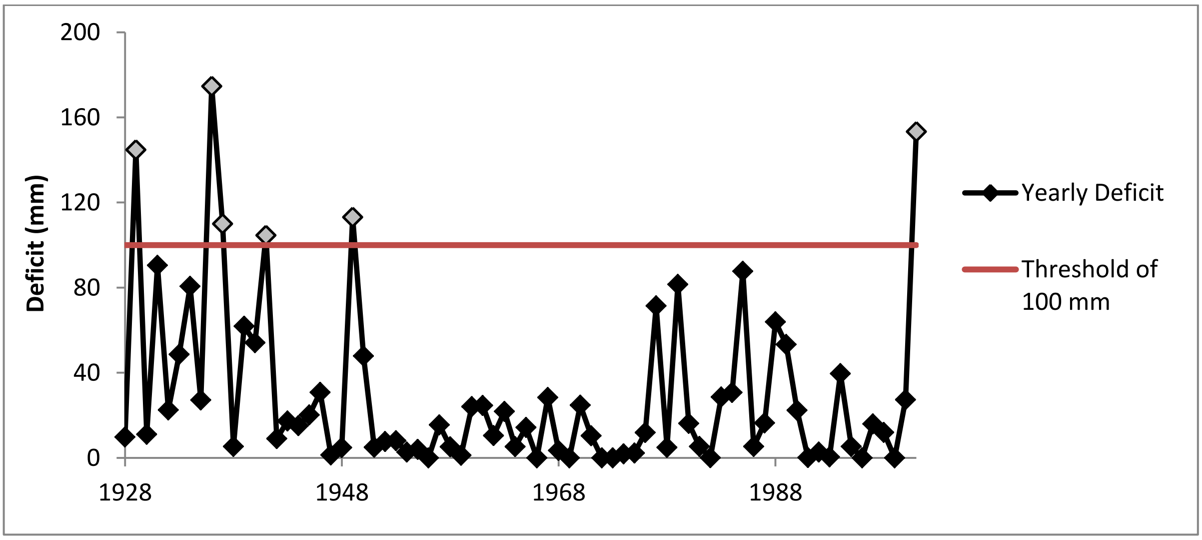


Figure 37: Reliability of a Series of Annual Water Deficits (unsatisfactory state indicated with lighter markers)

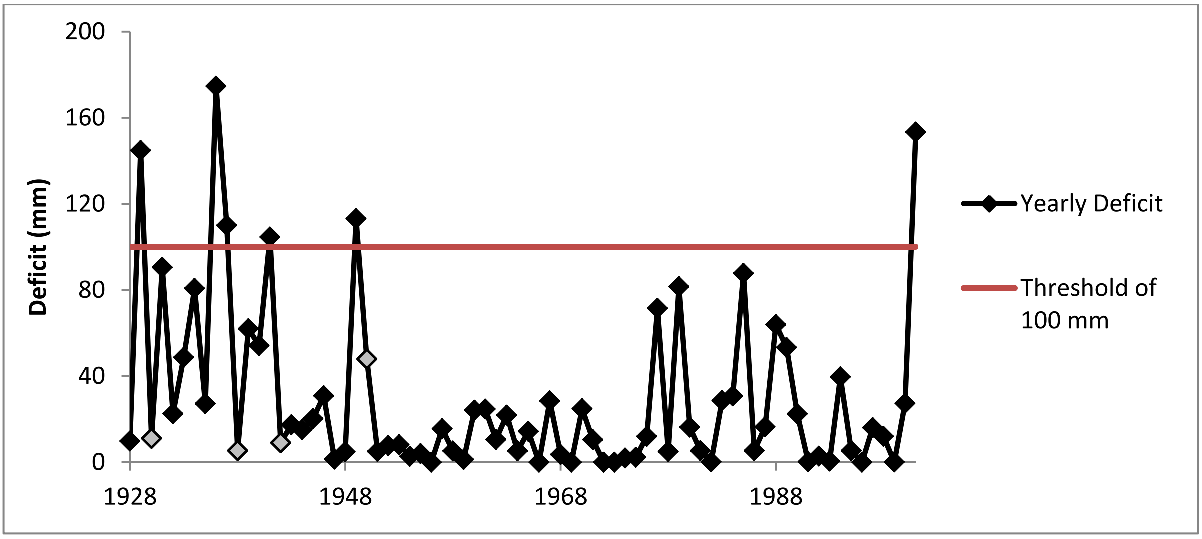


Figure 38: Resilience of a Series of Annual Water Deficits (acceptable water deficit following an unacceptable water deficit event indicated with lighter markers)

Previous studies simulating water supply management through the WRMM assessed water deficit performances by different criteria. For example, in their study on the SSRB water supply, AMEC (2009a) considered that scenarios were acceptable if the water deficits were above 100 millimeters in less than 10% of the year simulated or never for two consecutive years. In other words, scenarios having a reliability measure greater than 0.9 (90%) and having a resilience of 1 (100%) were considered acceptable. The IWMSC (2002a) determined irrigation regulations by evaluating the performances of various agriculture development scenarios. They tolerated water deficits equal or greater than 75 millimeters for less than 20% of the years simulated and water deficits equal or greater than 150 millimeters for less than 10% of the years simulated. Finally, AAF currently uses a reliability measure criterion, which allows water deficits equal or greater than 100 mm for less than 10% of the years simulated when they evaluate irrigation districts' expansion projects feasibility (Bob Riewe, personal communication, AAF, October 2014).

Therefore, in order to assess the severity of water deficits from one scenario to another, the following criteria were applied for the length of the simulation:

1. The timing of the water deficits is compared graphically by plotting the weekly water deficits of representative dry years;
2. The average magnitude of the water deficits is calculated for the study period;
3. The reliability, resilience and vulnerability of the water deficits is based on a threshold value of 100 mm separating the satisfactory from the unsatisfactory states;
4. A reliability equal or below 0.9 for any irrigation district is considered to lead to unacceptable water deficit risks.

In the WRMM, the water deficits are calculated by subtracting the water supply allocated from the ideal water demand. The water demand and supply values are given as weekly water depth (in mm) for each irrigation district's blocks and for each year simulated (1928 to 2001). Therefore, the annual water deficits (summation of all weekly values), the average water deficits and the risk measures of the deficits (reliability, resilience, and vulnerability) are calculated individually for each irrigation district's block and then aggregated for each irrigation district using the area-weighted factors presented in the Appendix D – Irrigation Districts' Blocks Area-weighted Factors.

5.1.3.2 Master Apportionment Agreement

The WRMM simulates the weekly South Saskatchewan River flow passing from Alberta to Saskatchewan. The flowrate sequence is in cubic meters per second for the river reach identified as "Appt Canal 104" in the Main SSRB WRMM sub-model. In order to calculate the yearly delivered volume of water from the weekly flow values, it has to be noted that the last week of the simulation cycle (week 52) has eight days instead of seven. Moreover, the South Saskatchewan River weekly natural flow data corresponding to the maximum volume of water that could be delivered to the Saskatchewan is indicated in the Hydrometeorological Base Data File (HBDF). The yearly percentage of the natural flow passing the border can then be calculated by dividing the simulated annual river discharge by the annual natural discharge. More particularly, the following values are estimated:

1. The average water delivery at the Saskatchewan border is calculated in cubic decametres for the study period;
2. The number of years for which less than 48% of the natural flow is delivered;
3. The number of years for which between 48 to 50% of the natural flow is delivered.

A scenario is considered to be acceptable if the volume of water delivered to Saskatchewan is greater than or equal to 48% of the natural flow for every year simulated (1928-2001). Indeed, even if the Master Apportionment Agreement requires a minimum volume of 50%, it is considered to be acceptable to obtain a slightly smaller volume for a few years (Tom Tang, personal communication, AEP, September 2014). However, the Master Apportionment Agreement performances of various scenarios can be further assessed by comparing the average volume of water delivered to Saskatchewan and the number of years when between 48 to 50% of the natural flow volume is delivered.

5.1.3.3 Diversion Rate in the Carseland Canal

Lowering the diversion rates in late summer, particularly in July and August, could improve the water quality in the Bow River for fish habitat. Indeed, reduced diversions allow higher river stage, which provides a buffer to minimize instream temperature increases and improve the river water quality. The province of Alberta considers water temperatures and dissolved oxygen to be the most critical variables to focus on in southern Alberta (AESRD 2003). Moreover, it was reported during the interviews with the water manager of the BRID that it is preferable to reduce the diversions in late summer by using the storage accumulated early in the season in order to preserve the water quality in the Bow River while slowly reaching the lower winter levels for the reservoirs (Richard Phillips, personal communication, BRID, August 2014).

Therefore, a scenario is considered to have a better environmental impact if the BRID's weekly diversions are reduced between weeks 27 (July 2nd - July 8th) and 35 (August 27th - September 2nd) when comparing representative normal years. The diversion rates can be analysed as the WRMM simulates the weekly water withdrawals from the Bow River to the BRID's diversion infrastructure (Carseland Canal). The simulated weekly diversion rates are given in cubic meter per second for the diversion canal identified as "Canal 420" in the Main SSRB WRMM sub-model.

5.1.4 Selection of Representatives Dry to Wet Years

When analysing the output of the WRMM model, scenario performances can be assessed by looking at specific years representative of dry to wet conditions. Indeed, simulation results such as reservoir levels, diversion rates or water deficits can be compared at a weekly scale for water stressed years (dry conditions), normal years and for surplus years (wet conditions). Moreover, the determination of the water supply available for dry to wet years is essential information in order to determinate the risks and trade-offs associated with irrigation sector management.

Irrigation management is based on the interaction between water supply and water demand as irrigated water is applied when the combination of precipitation and soil humidity are insufficient to meet the crops' water requirements. The water supply is highly variable due to the stochastic nature of the hydrologic and climatic conditions. The water demand is also variable according to the weather and crop-related factors.

Water-stressed years are generally characterized by lower water supply availability through reduced rainfall and river flows during the growing season, which coincides with increased irrigation demands. On the other hand, water-surplus years are expected to have an increased volume in rainfall and river flows while irrigation demands are low. Finally, the "normal" type of year translates into average water supply and water demand conditions.

For the study, a total of three years is selected to represent typical dry, normal and wet conditions. The selection of three years, specifically, permits mitigation of the impact of variation in initial conditions, such as initial reservoir storage levels or early-season soil moisture, as well as conditions that could have a combined effect on various parameters, both on the water supply and water demand level classification. For example, dry conditions could be caused by poor rainfall over the growing season or by low snowmelt runoff or by a combination of both. The selection of three years also limits the number of analysis years from the total of a 74 year period-of-record, but ensures that extreme low, high and average conditions are well-depicted.

In order to determine the three years representative of each climate condition, the streamflow data from Water Survey of Canada and irrigation demands from one of the IDM’s simulation were analysed. The Water Survey of Canada station on the Bow River at Calgary (05BH004) was used to collect historical flow records as it is located upstream of the three irrigation districts diverting water from the Bow River. More particularly, the seasonal river flowrate volume from April to October was calculated for each year on record from 1928 to 2001 as these years are the ones simulated by the WRMM. The years 1952 and 1953 were excluded as flow data were missing. The seasonal flow volume was used rather than the annual flow volume in order to isolate the water available for individual irrigation seasons. The month of April is normally the period at which the irrigation districts start to refill their reservoirs by capturing the spring snowmelt runoff and October is usually the last month at which irrigation takes place. The IDM’s simulated irrigation demands were area-weighted to obtain a single value representative of the yearly irrigation demand for the four irrigation districts combined (the WID, BRID, EID and LNID). The LNID does not divert water from the Bow River; however, it is simulated in the WRMM as its storage contributes to meet the Master Apportionment Agreement. The IDM’s simulation is based on a fixed crop mix and fixed irrigation equipment, but the model takes into account historical meteorological data such as rainfall volume and soil moisture conditions to estimate the weekly crop water requirements. Therefore, when the irrigation demand values are compared from one year to another, their variability is mostly influenced by weather factors. As a result, the irrigation demand time-series is a good indicator of low to high water demand years.

The series of years was classified by attributing to each year a rank from 1 to 72 in ascending order for the seasonal streamflow volumes and descending order for the irrigation demands. There are only 72 years considered, with the exclusion of the years 1952 and 1953. An ascending order is chosen for the streamflow analysis, because if the flow is greater, the supply available from river diversions will also be greater, which could be associated with surplus years. However, the irrigation demands are classified in descending order because if the irrigation demands are smaller, the need for irrigation will also be reduced, thus leading also to probable surplus year conditions. A total ranking value is calculated from the summation of the two ranks attributed for the streamflow volume and the irrigation demand. A year having an overall high rank with a river-flow volume above the upper quartile and an irrigation demand below the lower quartile of the dataset is associated generally with wet conditions while a year presenting an overall low ranking with seasonal runoff below the lower quartile and an irrigation demand above the upper quartile of the dataset would be representative of dry conditions, which is in accordance with AEP criteria defined to characterize the water supply forecast data (AEP 2015a). Moreover, it was decided that no consecutive years should be selected for a same type of year (dry, normal or wet) in order to cover a broader range of the historical data but additional dry years were selected to represent back to back drought conditions. The detailed streamflow volumes, irrigation demands and associated ranks for each year considered are presented in the Appendix E – Dry to Wet Years Classification.

Table 15 presents the five years having the lowest overall ranking, which correspond to low streamflow volumes and high irrigation demands. The year 2001 and 1949 were selected because of their lowest ranks representative of the driest conditions from the 72 years study period. Even if the year 2000 has the third lowest ranking, it has not been selected because as it was preferred to select a year from another dry period event. Therefore, the year 1936 was selected as it was the next year having the lowest overall ranking. Moreover, the year 1937 was selected as the second consecutive dry year combined with 1936 when extending drought conditions are analysed. Similarly, the year 2000 was selected as the first back to back dry year combined with 2001. Note that all the selected years fall below the lower quartile of the seasonal streamflow volume and above the upper quartile of the annual simulated irrigation demands.

Table 15: Dry Years Selection Based on Seasonal Streamflow Volume and Area-Weighted Irrigation Demand Depth

Year - Dry	Seasonal Volume April – October (dam^3)	Seasonal Volume Rank	Area-Weighted Irrigation Demand (mm)	Irrigation Demand Rank	Total Rank
2001*	1 376 628	1	526	1	2
1949*	1 506 807	5	439	7	12
2000**	1 651 216	9	451	6	15
1936*	1 710 508	14	470	4	18
1937**	1 674 406	11	435	9	20
Mean	2 103 676		351		71
Upper Quartile	2 362 193		403		98
Lower Quartile	1 796 877		311		44

* Selected year for representative dry conditions
** Additional years to simulate consecutive dry years

Table 16 presents the five years having the highest overall ranking, which correspond to high streamflow volumes and low irrigation demands. The year 1965 and 1981 were selected because of their highest ranks. The year 1928 was not selected because it is the first year of the simulation. Indeed, some of the model outputs simulated for this particular year could be influenced by the pre-defined initial reservoir storage values. The year 1966 was not selected as well, because the year 1965 has already been selected and it was preferred to cover a broader range of the data time-series. Therefore, the year 1954 was a more appropriate choice. All the wet years indicated correspond to streamflow volume values above the upper quartile and irrigation demands below the lower quartile.

Table 16: Wet Years Selection Based on Seasonal Streamflow Volume and Area-Weighted Irrigation Demand Depth

Year - Wet	**Seasonal Volume April – October (dam^3)**	**Seasonal Volume Rank**	**Area-Weighted Irrigation Demand (mm)**	**Irrigation Demand Rank**	**Total Rank**
1965*	2 730 331	65	208	67	132
1981*	2 859 719	68	287	61	129
1928	3 273 709	70	306	57	127
1966	2 474 453	56	208	68	124
1954*	3 024 156	69	310	54	123
Mean	2 103 676		351		71
Upper Quartile	2 362 193		403		98
Lower Quartile	1 796 877		311		44

* Selected year

The years presented in Table 17 are those having an overall ranking close to 71 the average total ranking attributed. A broader range of years were analysed to determine the representative normal conditions from the rank 61 to the rank 81. Indeed, it is necessary that the representative normal year conditions have both average seasonal flow volumes and average irrigation demands contained within the normal range delimited by the lower and upper quartile of each dataset. As a result, the normal years should not be selected solely on how close their total ranking is to the average rank value. For example, a given year could have a very high seasonal flow volume (high rank for the water supply criterion) and high irrigation demand (low rank for the water demand criterion), which would translate in an average overall ranking but would not be representative of average hydrological and climatic conditions. A good example is the year 1933, which has a seasonal streamflow volume above the upper quartile and an irrigation demand also above the upper quartile, which is far from average conditions. Based on their seasonal flow and irrigation demand ranking, the years selected are 1959, 1962 and 1964. The year 1958 would have been a good choice as well, because it has a streamflow volume and irrigation demand values slightly closer to the mean values compare with the year 1959. It was nevertheless considered judicious to select the year 1959 as it is the second year in a row representing average hydrological and meteorological conditions. This means that the initial reservoir storage for starting the irrigation season is probably representative of a normal storage level.

Table 17: Normal Years Selection Based on Seasonal Streamflow Volume and Area-Weighted Irrigation Demand Depth

Year - Normal	Seasonal Volume April – October (dam^3)	Seasonal Volume Rank	Area-Weighted Irrigation Demand (mm)	Irrigation Demand Rank	Total Rank
1971	2 098 146	37	377	24	61
1973	2 072 848	36	371	25	61
1935	2 268 907	50	412	13	63
1955	2 056 510	34	361	30	64
1962*	2 039 381	33	357	32	65
1997	1 937 663	28	350	37	65
1930	2 364 565	53	411	14	67
1933	2 525 576	58	435	10	68
1982	1 850 701	23	322	46	69
1958	2 114 748	38	353	34	72
1959*	1 983 779	31	335	42	73
1975	1 674 933	12	261	63	75
1964*	2 204 608	43	350	36	79
1967	2 680 525	63	404	18	81
1980	1 941 088	29	312	52	81
Mean	2 103 676		351		71
Upper Quartile	2 362 193		403		98
Lower Quartile	1 796 877		311		44

* Selected year

Figure 39 to Figure 41 show the Bow River streamflow at Calgary for the three years selected to represent dry, normal and wet conditions as well as the mean discharge from the 72 year study period. The errors bars indicate the standard deviation of the streamflow time-series.

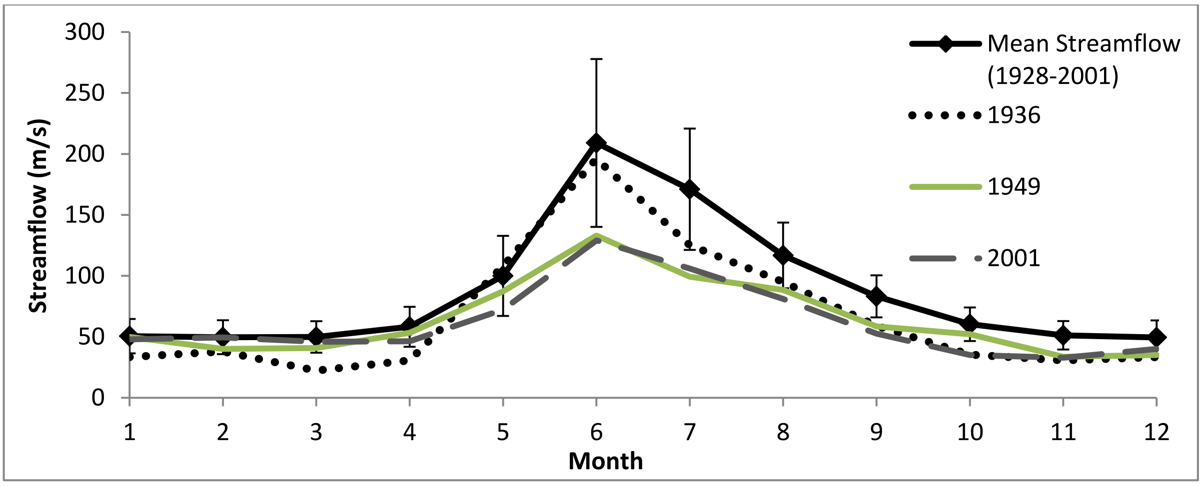


Figure 39: Mean Monthly Streamflow over the Study Period (1928-2001) and for Three Historical Dry Years (1959, 1962, 1964) for the Bow River at Calgary (Adapted from Water Survey of Canada 2014)

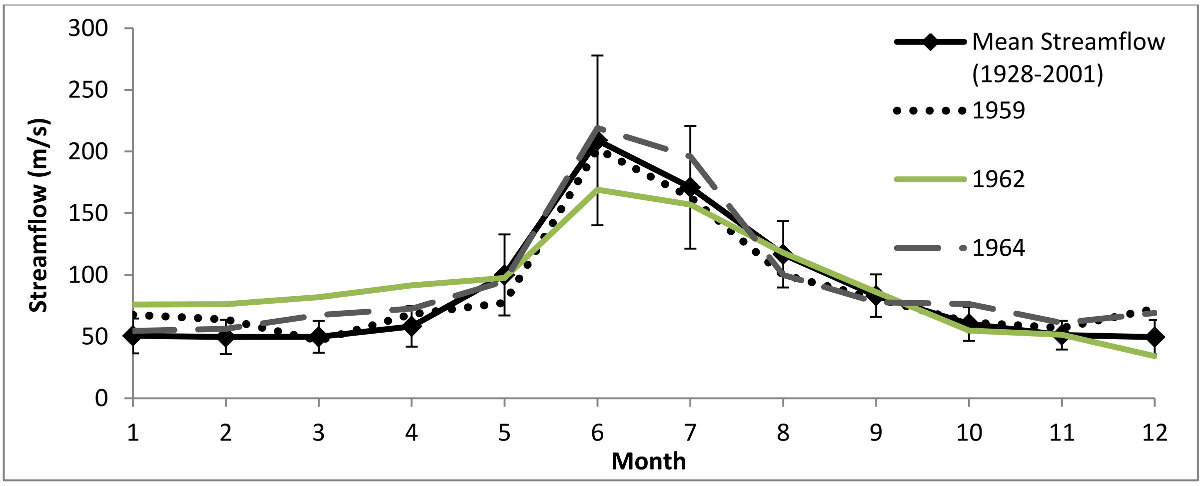


Figure 40: Mean Monthly Streamflow over the Study Period (1928-2001) and for Three Historical Normal Years (1959, 1962, 1964) for the Bow River at Calgary (Adapted from Water Survey of Canada 2014)

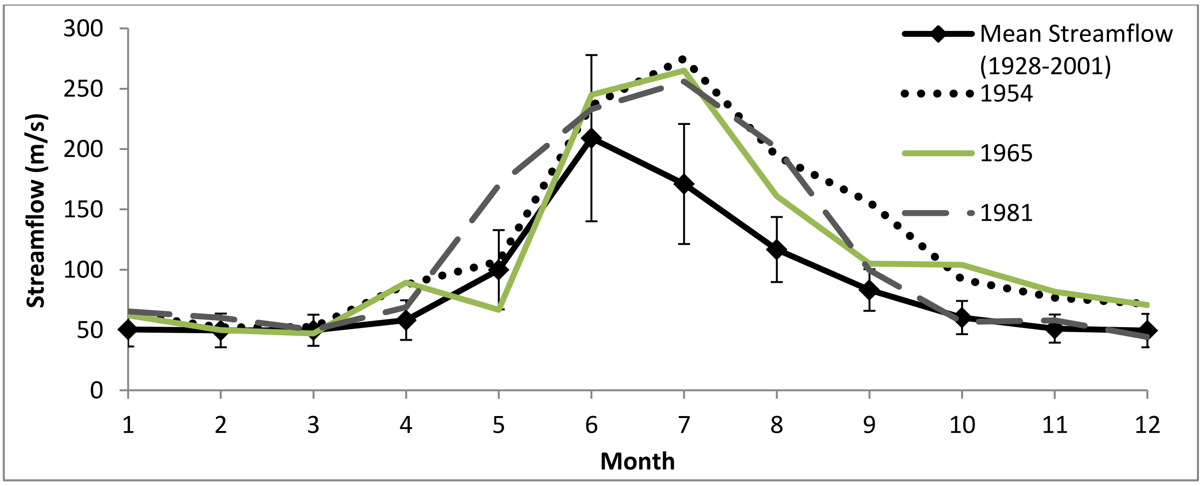


Figure 41: Mean Monthly Streamflow over the Study Period (1928-2001) and for Three Historical Wet Years (1959, 1962, 1964) for the Bow River at Calgary (Adapted from Water Survey of Canada 2014)

Figure 42 and Figure 43 present the probability of exceedance of the mean monthly flows in the Bow River at Calgary for the months of April to October and the area-weighted irrigation demands for the four irrigation districts. Moreover, the data corresponding to the years selected to represent dry, normal and wet conditions are indicated. As shown graphically, the years selected cover generally the extreme values of the time-series (smallest and greatest probability of exceedance) as well as the average values (probability of exceedance around 0.5).

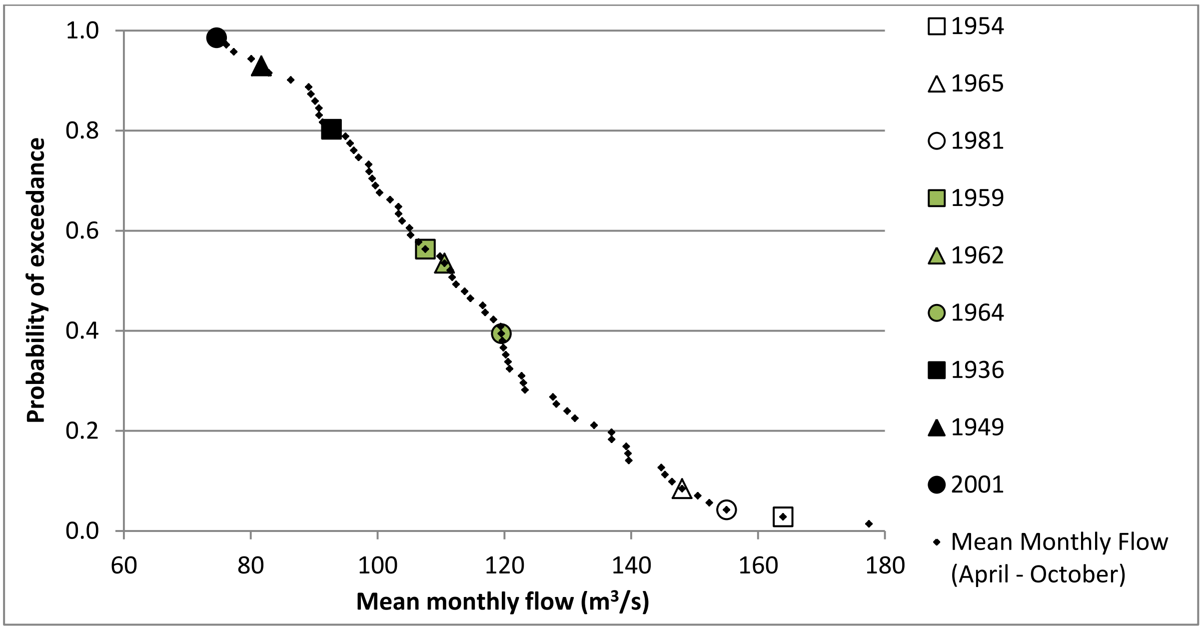


Figure 42: Cumulative Frequency Plot of the Seasonal Mean Streamflow (April-October) for the Bow River at Calgary from 1928 to 2001 (Adapted from Water Survey of Canada 2014)

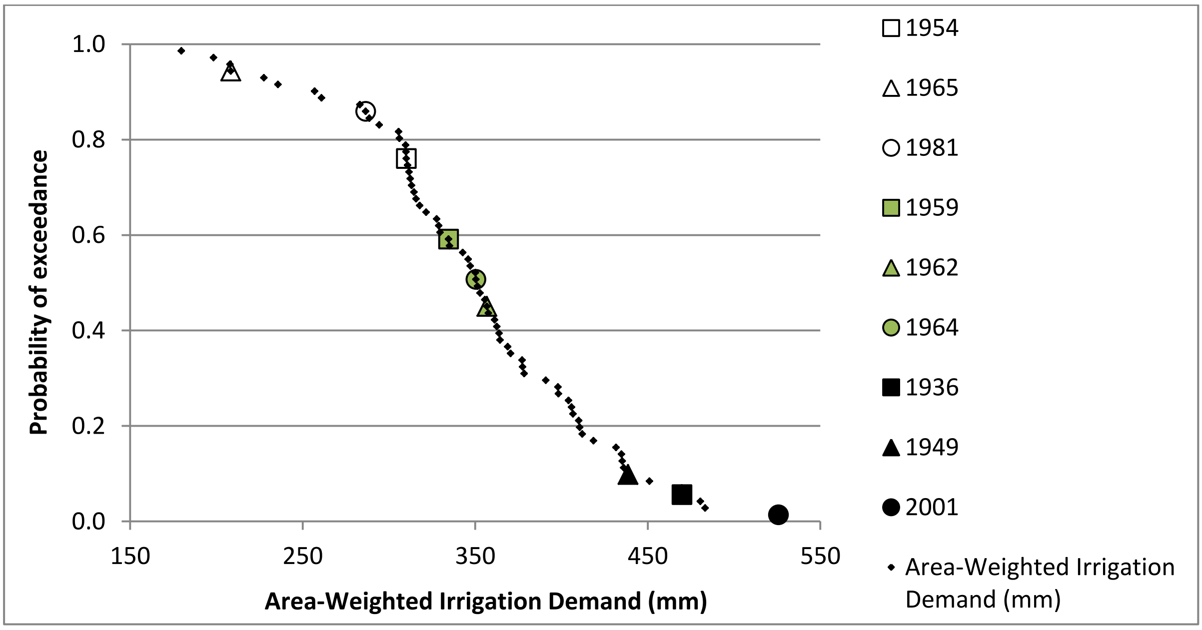


Figure 43: Cumulative Frequency Plot of the Area-Weighted Irrigation Demands for the 2012's Expansion Limit, Crop Mix and Irrigation Efficiency Simulated by the IDM from 1928 to 2001

5.2 Results and Discussion: BRID Reservoir Management and its Impact on the Bow River Basin

The performance of the Original WRMM and the scenarios representing changes in the reservoirs ideal curves, McGregor minimum operating zone and the penalty associated with the operating zones of the BRID reservoir system are compared in this section. The goal of this analysis was to assess whether the model results could be improved by alternative reservoir management strategies.

5.2.1 Updating the Ideal Curves of the Reservoirs

The first objective of the reservoir management analysis was to determine the impact of updating the reservoir ideal curves in the WRMM model to represent more realistically the current operational constraints of the BRID reservoirs. Therefore, the hypothesis guiding the results analysis is as follows:

1. Updating the ideal curves in the WRMM model to represent current operations in the BRID would reduce the water supply available to meet water demands.

To validate or invalidate the first hypothesis, the Original WRMM scenario is compared with the Updated Ideal Curves scenario. The performance assessment of these two simulations permits isolation of the impact of updating the ideal curves without changing any other parameters.

5.2.1.1 Simulated Water Supply

The comparison of the average water supply for the length of the simulation (1928-2001), and for the four districts simulated in the model – WID, BRID, EID and LNID – are presented in Table 18. The simulation results are on average practically the same for both scenarios. Indeed, changing the BRID ideal curves to account for recent erosion problems and flood mitigation management directives reduces only slightly the supply available for the BRID from 396.7 to 396.1 mm per unit area on average. There is practically no impact on the other districts as the Updated Ideal Curves scenario increases the supply per unit area of the WID and the EID by about a tenth of a millimetre on average. The small difference in water supply is a consequence of the districts' junior licences. Indeed, the WID and the EID main licences have seniority over the BRID main licence, but the districts also have smaller junior licences, which are subject to river stage and the Instream Objectives. If the BRID diverts less water to refill its reservoirs, which are maintained lower in the Updated Ideal Curves scenario, more water become available for the WID or the EID diversions.

Table 18 : Simulated Average Water Supply (1928-2001) Available to Meet the Irrigation Demand by the Original WRMM and the Updated Ideal Curves Scenarios

Irrigation District	Original WRMM		Updated Ideal Curves		Difference
	(mm)	(dam^3)	(mm)	(dam^3)	(mm)
WID	320.6	123,260	320.7	123,301	0.1
BRID	396.7	417,361	396.1	416,797	-0.5
EID	418.7	526,907	418.8	527,083	0.1
LNID	296.9	272,735	296.9	272,711	-0.0
Total	370.9	1,340,263	370.8	1,339,892	-0.1

5.2.1.2 Risk Measures of the Water Deficits

As the water supply results were practically the same for both scenarios, the risk measures characterizing the water deficits were also similar as shown by Table 19. Both scenarios have the same reliability and resilience performances but have small differences in terms of vulnerability. Indeed, changing the ideal curves of the BRID's reservoirs increases the BRID vulnerability by about 9 mm on average for the years when its water deficits are greater than 100 mm.

Table 19 : Risk Measures of the Water Deficits (1928-2001) for the Original WRMM and the Updated Ideal Curves Scenarios

Irrigation District	Reliability		Resilience		Vulnerability	
	Original WRMM	Updated Ideal Curves	Original WRMM	Updated Ideal Curves	Original WRMM	Updated Ideal Curves
WID	0.92	0.92	0.91	0.91	35.24	35.01
BRID	0.99	0.99	1.00	1.00	25.92	34.48
EID	0.98	0.98	0.95	0.95	16.75	16.67
LNID	0.88	0.88	0.73	0.73	81.21	81.40
Total	0.95	0.95	0.90	0.90	37.77	40.26

5.2.1.3 Typical Dry Years Water Deficits

The difference in the magnitude of the BRID's average water deficit is more noticeable during dry years as shown by the comparison of Table 20 and Table 21. Table 20 presents the yearly deficits during three typical dry years while Table 21 presents the results for three typical normal years. The Updated Ideal Curves scenario generates higher deficits for the BRID in dry years, but can reach the same performance as the Original WRMM during normal years. Moreover, even if the deficits are greater in the dry years of 1936 and 1949 for the BRID, they are still reasonable as they fall below the threshold value of 100 mm. In the case of 2001, changing the BRID's ideal curves increases its seasonal water deficit from 105 mm to 113 mm, but it is the only year in which this district experiences severe deficits for both scenarios. These results confirm that even if the reservoir ideal curves had been lowered in the BRID to be more representative of the current operations, the water supply available is still sufficient to meet approximately the same demand as the Original WRMM.

Table 20: Simulated Water Deficits for Three Typical Dry Years by the Original WRMM and the Updated Ideal Curves Scenarios

	1936 Area-Weighted Deficit (mm)			1949 Area-Weighted Deficit (mm)			2001 Area-Weighted Deficit (mm)		
Irrigation District	Original WRMM	Updated Ideal Curves	Diff. with Reference	Original WRMM	Updated Ideal Curves	Diff. with Reference	Original WRMM	Updated Ideal Curves	Diff. with Reference
WID	174.6	174.6	0.0	113.4	113.4	0.0	153.3	153.3	0.0
BRID	24.6	38.7	14.1	10.6	9.8	-0.9	105.1	113.1	8.0
EID	81.9	81.9	0.0	39.7	39.8	0.0	89.1	89.0	-0.1
LNID	192.4	192.8	0.4	60.1	60.1	0.0	297.3	297.3	0.0
Total	103.2	107.4	4.2	43.3	44.0	-0.3	153.5	155.8	2.3

Table 21: Simulated Water Deficits for Three Typical Normal Years by the Original WRMM and the Updated Ideal Curves Scenarios

	1959 Area-Weighted Deficit (mm)			1962 Area-Weighted Deficit (mm)			1964 Area-Weighted Deficit (mm)		
Irrigation District	Original WRMM	Updated Ideal Curves	Diff. with Reference	Original WRMM	Updated Ideal Curves	Diff. with Reference	Original WRMM	Updated Ideal Curves	Diff. with Reference
WID	1.2	1.2	0.0	10.5	10.5	0.0	5.3	5.3	0.0
BRID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EID	0.0	0.0	0.0	15.9	15.9	0.0	0.0	0.0	0.0
LNID	1.5	1.5	0.0	39.4	39.4	0.0	18.0	18.1	0.0
Total	0.5	0.5	0.0	16.7	16.7	0.0	5.2	5.2	0.0

Figure 44 presents graphically the difference in weekly deficits for the BRID during the 2001 dry year. As shown, the timing and magnitude of the deficits are similar for both scenarios. The deficits are only increased by a few millimeters during weeks 32 and 35.

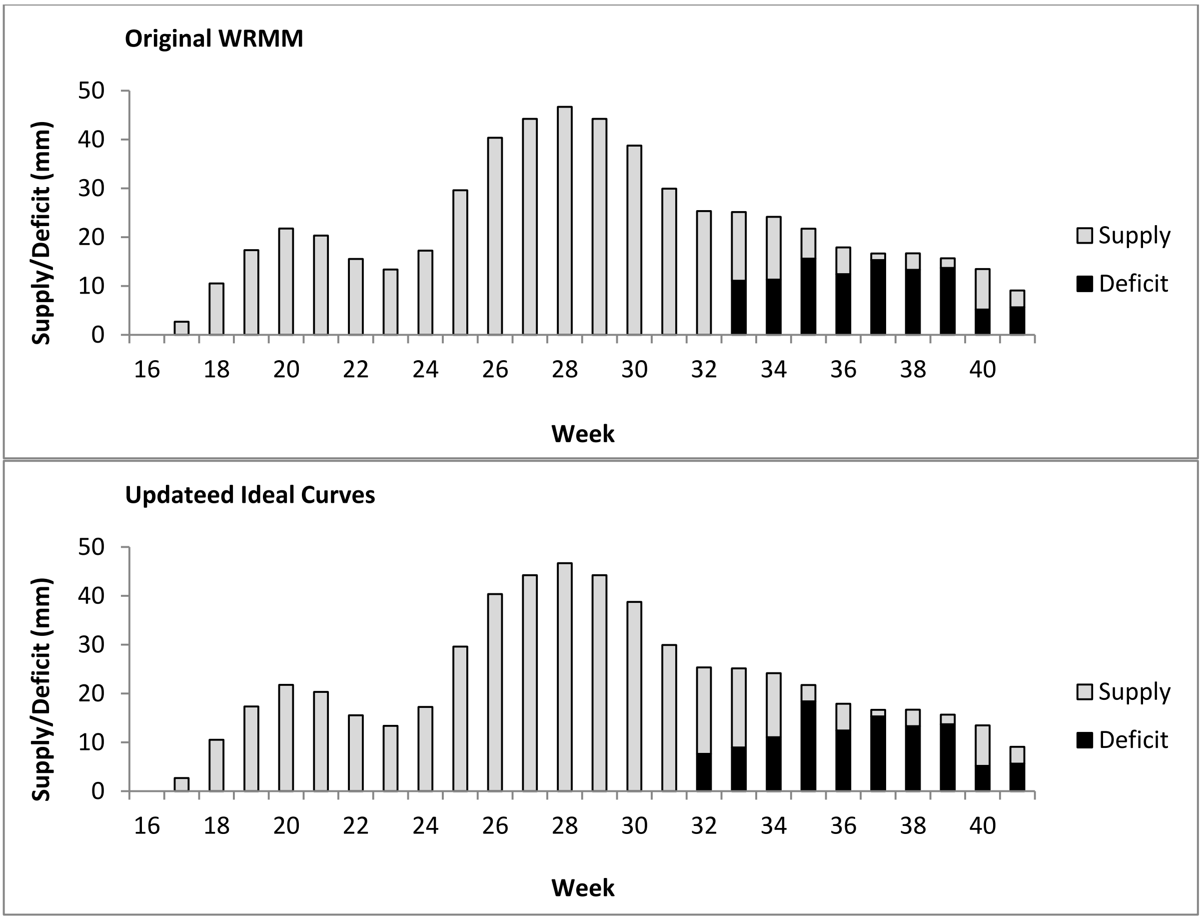


Figure 44: Simulated BRID's Weekly Area-Weighted Deficits during a Typical Dry Year (2001) by the Original WRMM and the Updated Ideal Curves Scenarios

Figure 45 shows McGregor Reservoir's levels during the dry years of 2000 and 2001 simulated by the two scenarios as well as the historical data reported by AEP. Notice that even if McGregor reservoir is maintained lower in the Updated Ideal Curves scenario, its weekly elevations are higher in summer compared to the Original WRMM. Indeed, as Travers-Little Bow reservoir is also lowered to meet its flood mitigation objectives in the Updated Ideal Curves scenario, more water becomes available to refill McGregor. However, in both scenarios McGregor available storage is depleted severely in late July (week 29 in 2000 and week 79 in 2001), which explains the BRID's deficits occurring toward the end of the growing season as presented above by Figure 44.

The historical data are indicated in order to provide real-world comparison data, but they represent different irrigation conditions than the simulations analysed. It is still interesting to note that the historical level reached in the winter 2000-2001 is particularly higher than the one simulated by both scenarios even if the summer level measured in 2000 is close to the simulation results and finally, the reservoir is drawn down much lower in 2001 than in the simulations. The results show that McGregor Reservoir's simulated storage level variations do not correspond to real-world operations.

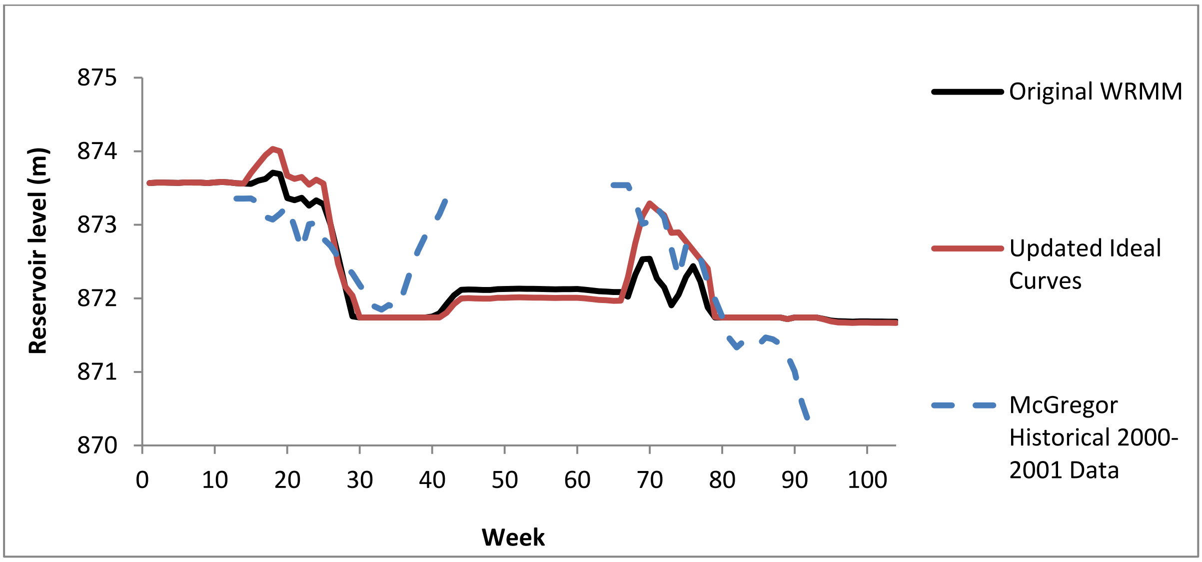


Figure 45: Weekly McGregor Reservoir Levels during Two Consecutives Dry Years (2000-2001) Simulated by the Original WRMM and the Updated Ideal Curves Scenarios

5.2.1.4 Master Apportionment Agreement Performance

In terms of meeting the Master Apportionment Agreement, updating the BRID's ideal curves reduced the yearly flow at the Saskatchewan border of about 350 dam^3 on average compared to the results obtained by the Original WRMM. For specific years, the percentage of the natural flow that is delivered can be increased or decreased by about 27,500 dam^3. This variation represents only about 0.3% of the total flow that crosses the border, which is 8,609,073 dam^3 on average for the study period (1928-2001). In both cases, the scenarios did not deliver more than 48% of the natural flow in the drought of 2001; the Original WRMM delivered 47.12% and the Updated Ideal Curves 47.18%. Moreover, the Updated Ideal Curves scenario flows remained below 50% for two additional years (1931 and 1937) while the Original WRMM scenario delivered flow was fewer than 50% only for one more year (1931). The difference between the two simulations is however small; the flow delivered in 1937 changed from 50.11% in the Original WRMM scenario to 49.99% in the Updated Ideal Curves scenario. Again, it is considered that both scenarios generated similar results.

5.2.1.5 BRID's Diversion Rates

Figure 46 presents the BRID's average weekly diversions for the three typical normal years (1959, 1962, and 1964). In July (weeks 27 to 30) and in August (week 31 to 34), both scenarios generated the same diversion rates. However, the Original WRMM diversions are slightly lower in September (week 35 to 39), which could be more beneficial for the river stage downstream of the BRID. In the Updated Ideal Curves scenario, the BRID's reservoirs are maintained lower and thus, some of the late irrigation demand has to be met with additional diversions from the river compared to the

Original WRMM. Furthermore, the diversion is lower at the beginning of the irrigation season from the week 16 to 21 under the Updated Ideal Curves scenario, because less water is necessary to refill Travers-Little Bow reservoir, which is maintained lower for flood mitigation purpose.

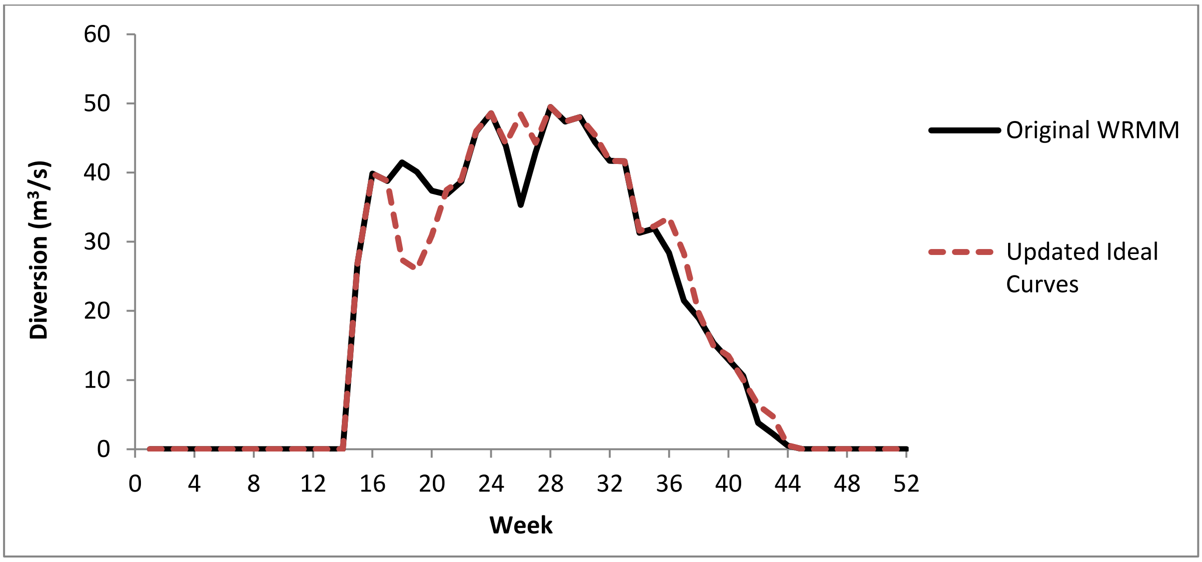


Figure 46: BRID's Average Weekly Diversion Rate in Carseland Canal for Three Typical Normal Years Simulated by the Original WRMM and the Updated Ideal Curves Scenarios

5.2.1.6 BRID's Average Reservoir Levels

Figure 47 shows the BRID's average reservoir levels for the two scenarios assessed as well as the historical data. The historical data are based on a limited number of years, particularly for the BRID's internal reservoirs, and do not capture recent changes in operations that have occurred in the district. Moreover, as the irrigation demands simulated are different from the historical ones, a scenario is not considered to give a better representation of the current operations exclusively if the average level lay closer to the historical data, but it still provides an interesting comparison. The historical levels of Travers reservoir are also indicated even if the WRMM simulated Travers-Little Bow reservoir, because their minimum and maximum operating levels are similar.

The average reservoir levels simulated by the Updated Ideal Curves scenario are generally lower as a consequence of the ideal curves representative of the current district's practices. McGregor's and Travers-Little Bow's simulated winter levels tend to be lower than the ones indicated by the historical data, but it could be a consequence of data survey problems in colder months. Interestingly, even if the ideal curve for McGregor in winter is exactly the same for both scenarios, the winter levels obtained from the Updated Ideal Curves simulation are on average lower than the Original WRMM. The fact that the 1st relaxation zone of McGregor has the lowest penalty explains this result as the model will draw down this reservoir zone before it draws down any other.

Therefore, McGregor storage is partly used to compensate for the slightly reduced storage available under the Updated Ideal Curves scenario. Moreover, Badger and Scope simulated reservoir levels are generally higher than what was observed in the field, particularly in mid- to late summer and in the case of the Original WRMM version. These reservoirs have the highest penalty of the BRID reservoir system, which ensures they are maintained closer to their ideal level and explains this difference with the observed data. Lastly, Badger simulated reservoir levels from the Updated Ideal Curves scenario are on average closer to the recorded levels as the ideal curve simulated represents better the current operational guidelines of this reservoir.

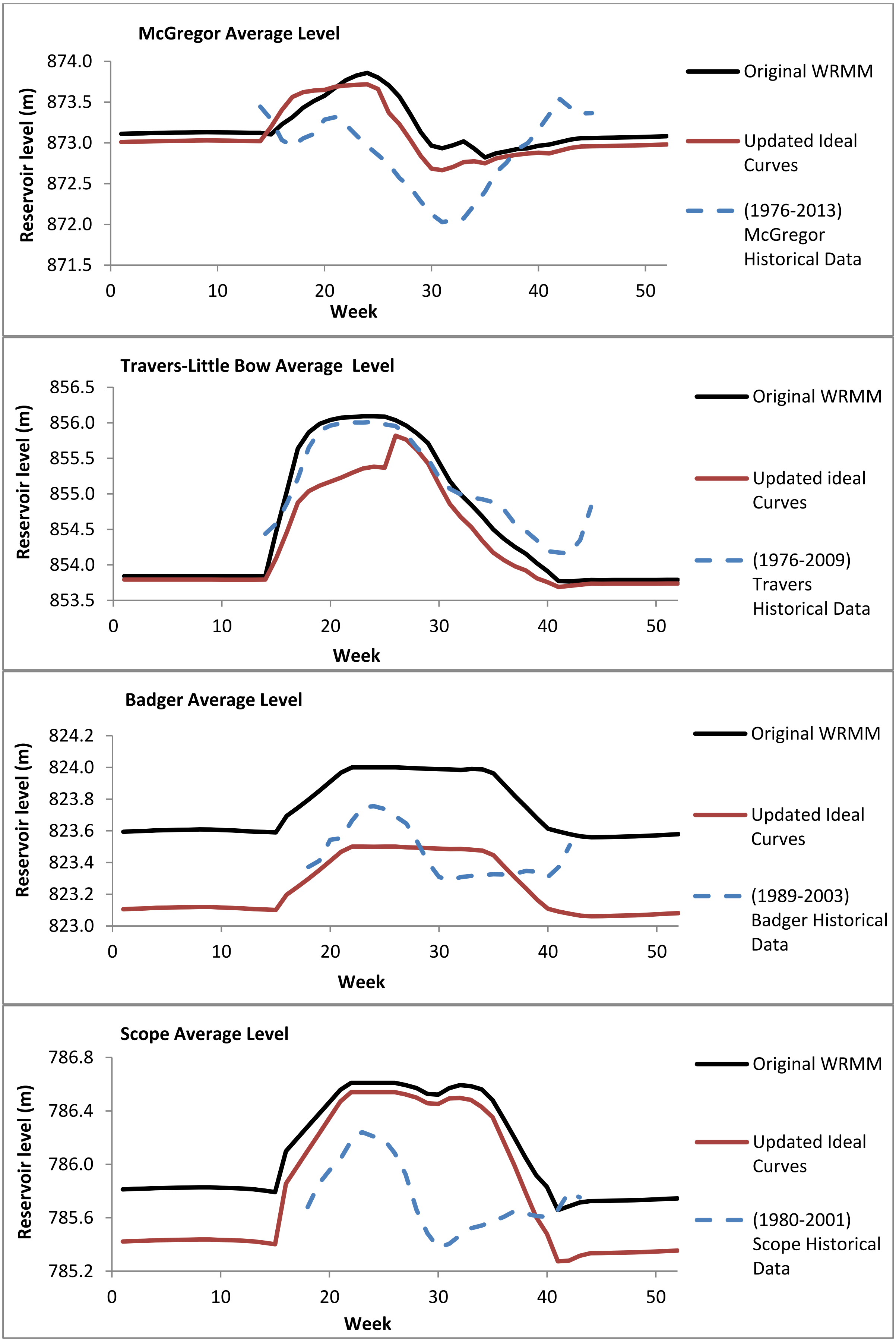


Figure 47: Simulated BRID's Reservoir Average Levels by the Original WRMM and the Updated Ideal Curves Scenarios

5.2.1.7 Assessment of the Hypothesis

It was believed that updating the ideal curves in the WRMM model to represent more adequately the current operations in the BRID would reduce the water supply available to meet irrigation demand. However, based on the simulation results of the average water supply, the risk measures of the water deficits, the Master Apportionment Agreement, and the diversion rate in normal years, the first hypothesis of the reservoir management analysis is invalidated. Only a slight increase in magnitude of the water deficits occurred for the BRID, because less water was available through reservoir storage during dry years. However, as this district suffers small deficit recurrence, no additional impact for irrigation is considered under the Updated Ideal Curves scenario. Indeed, the performance difference between both scenarios was negligible in terms of evaluating the risks for irrigation management.

5.2.2 Simulation of Real McGregor Dead Storage

The second objective of the reservoir management analysis was to determine whether WRMM performance could be improved by changing the artificially-high minimum operating zone of McGregor Reservoir to its real dead storage level. The second and third hypothesises guiding the results analysis are then as follows:

2. Replacing McGregor's minimum operating zone for its dead storage level in the WRMM model to represent more realistically McGregor's total storage availability would increase the overall water supply available to meet water demand even if back to back dry years performances could be affected;
3. Combining the updated ideal curves in the WRMM model and McGregor real dead storage in the BRID would produce different water deficit performances from the Original WRMM, which could improve the modelling results accuracy for irrigation management studies.

To validate or invalidate the second hypothesis the Original WRMM is compared with the McGregor Dead Storage scenario while the third hypothesis is analysed by comparing the Original WRMM with the Current Management scenario.

5.2.2.1 Simulated Water Supply

The comparison of the average water supply provided by each scenario is presented in Table 22. The simulated supply is on average slightly higher when McGregor dead storage is used as the minimum operating level. Indeed, the supply available for the BRID increases from 396.7 to 398.3 mm per unit area on average. The other districts' water supply is also slightly improved but the difference is only on the order of a few tenths of a millimetre when the supply is averaged over the study period. The small differences in water supply are a consequence of the districts' junior licences in the case of EID and WID and the Master Apportionment Agreement in the case of LNID. If the BRID is diverting less water, because more of McGregor storage could be drawn down, more water becomes available for the WID or the EID junior diversions as well as to meet the Master Apportionment Agreement through return flows, which is beneficial to the LNID as well.

The simulated water supply for the Current Management scenario is mostly the same as the McGregor Dead Storage scenario. This confirms again that updating the BRID's reservoir ideal curves to represent better the current operations has minor impact on the simulated supply as shown in the previous section. The average supply is slightly greater for the BRID when the real McGregor dead storage is combined with the current ideal curves compare with solely modelling McGregor dead storage (419,149 dam^3 compare with 419,061 dam^3). Indeed, maintaining Travers-Little Bow reservoir lower at the beginning of the summer contributes to refill McGregor earlier and increased the overall water availability.

Table 22 : Simulated Average Water Supply (1928-2001) Available to Meet Irrigation Demand by the Original WRMM, the McGregor Dead Storage and Current Management Scenarios

Irrigation District	Original WRMM		McGregor Dead Storage		Difference with Original	Current Management		Difference with Original
	(mm)	(dam^3)	(mm)	(dam^3)	(mm)	(mm)	(dam^3)	(mm)
WID	320.6	123,260	320.9	123,389	0.3	320.9	123,376	0.3
BRID	396.7	417,361	398.3	419,061	1.6	398.4	419,149	1.7
EID	418.7	526,907	418.8	527,064	0.1	418.8	527,081	0.1
LNID	296.9	272,735	297.1	272,889	0.2	297.0	272,809	0.1
Total	370.9	1,340,263	371.5	1,342,404	0.6	371.5	1,342,416	0.6

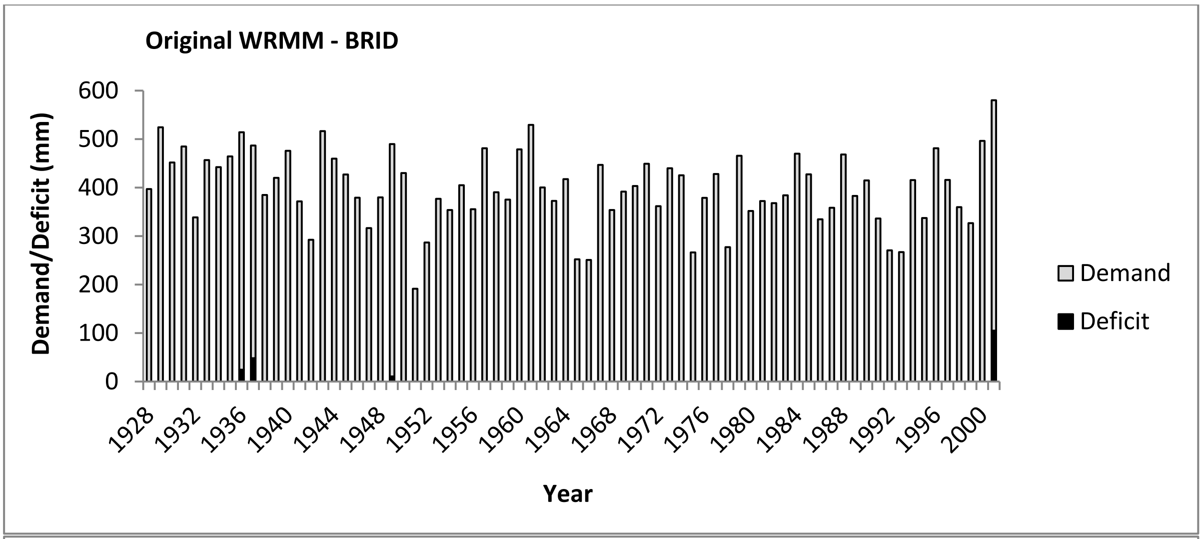
5.2.2.2 Risk Measures for the Water Deficits

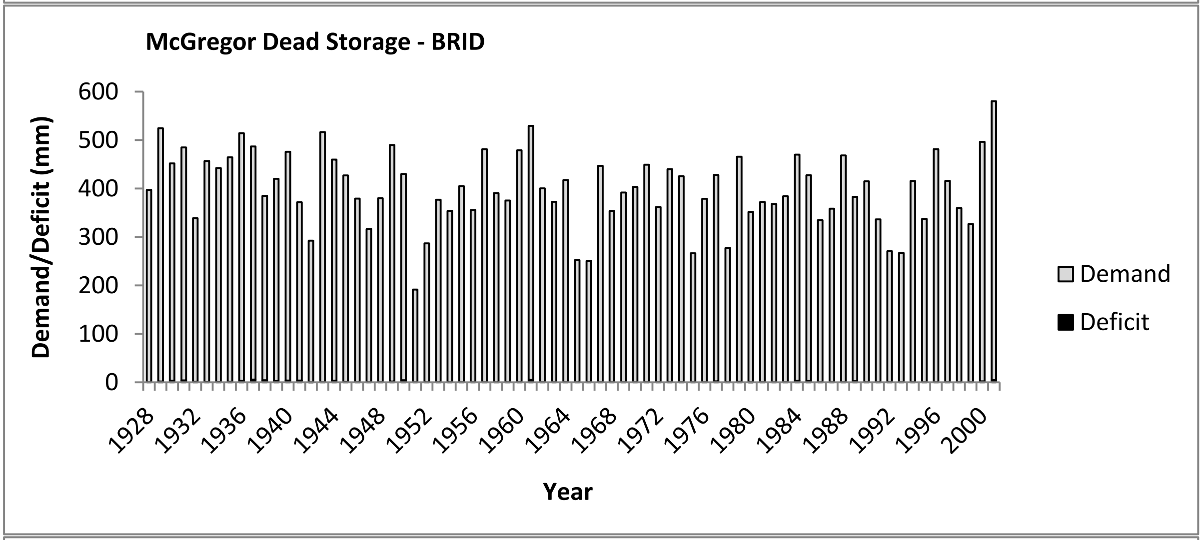
The risk measures characterizing the water deficits are presented by Table 23 for the three scenarios analysed. The scenarios have the same reliability and resilience performances for the four district's area-weighted deficits. However, the vulnerability of the BRID is reduced by about 24 mm when McGregor dead storage is simulated as the lowest operating zone. This means that the additional storage availability reduces considerably the severity of the water deficits for the years when the shortages are greater than 100 mm. However, the downside of emptying McGregor is the higher deficit risks for the Irrigation Block 339 diverting water directly from McGregor Reservoir, also indicated in Table 23. This block had no water deficit higher than 100 mm in any of the year simulated for the Original WRMM scenario; on the other hand, when McGregor's lowest operating zone is changed, this block experiences shortages greater than 100 mm for 26% of the simulated years (reliability of 0.74). Furthermore, the magnitude of the deficits simulated for the Block 339 are about 272 mm on average (vulnerability of 172 mm) and happen in back to back years half of the time (resilience of 0.47). The water demand of this block is still a small portion of the BRID's total water demand. The irrigated land of Block 339 represents only 1.2% of the district's total area (1,312 *versus* 105,221 hectares). Moreover, Block 339's performance is slightly improved when the dead storage of McGregor Reservoir is combined with the updated ideal curves in the Current Management scenario. Indeed, as the other BRID reservoirs are maintained lower in the Current Management scenario, more water could be used to refill McGregor Reservoir, which diminishes the diversion cut-off for Block 339. It could be concluded that simulating McGregor dead storage is generally beneficial for all the districts, but penalizes considerably the irrigators of Block 339.

Table 23 : Risk Measures of the Water Deficits (1928-2001) for the Original WRMM, the McGregor Dead Storage and the Current Management WRMM Scenarios

Irrigation District	**Original WRMM**		
	Reliability	**Resilience**	**Vulnerability**
WID	0.92	0.91	35.24
BRID	0.99	1.00	25.92
EID	0.98	0.95	16.75
LNID	0.88	0.73	81.21
Block 339	1.00	1.00	0.00
Total	0.95	0.90	37.77
Irrigation District	**McGregor Dead Storage**		
	Reliability	**Resilience**	**Vulnerability**
WID	0.92	0.91	34.41
BRID	1.00	0.99	2.14
EID	0.98	0.95	16.31
LNID	0.89	0.78	85.48
Block 339	0.74	0.47	172.02
Total	0.95	0.91	31.70
Irrigation District	**Current Management**		
	Reliability	**Resilience**	**Vulnerability**
WID	0.92	0.91	34.92
BRID	1.00	0.99	1.76
EID	0.98	0.95	16.49
LNID	0.89	0.78	86.54
Block 339	0.74	0.53	141.33
Total	0.95	0.91	31.97

Figure 48 and Figure 49 show graphically the yearly area-weighted deficits of the BRID's blocks and the yearly water deficits of the Block 339 alone for the length of the study period (1928-2001). Note how the greater storage available through McGregor Reservoir in the alternative scenarios reduced overall the BRID's water deficits at the cost of decoupling Block 339's deficits. Particularly for the years 1937 and 1938, the block is unable to divert any amount of water, which could lead to severe economic impacts. The water unallocated to this block under the modified reservoir management scenarios can be used to meet the demand of the other BRID irrigation blocks downstream of McGregor Reservoir; however, Block 339's demand is small in comparison with the volume of water contained in McGregor Reservoir below the level at which the irrigators experience pumping difficulties. As a result, the additional water deficits experienced by Block 339 correspond only to about 1.4% of the additional water that is provided to the entire BRID network during the year 1936 and 1937 under the McGregor Dead Storage and Current Management scenarios. It can be concluded that the higher and more frequent deficits experienced by Block 339 are not a consequence of a lack in water supply available, but are rather due to the physical limitations of this block's water diversion system.





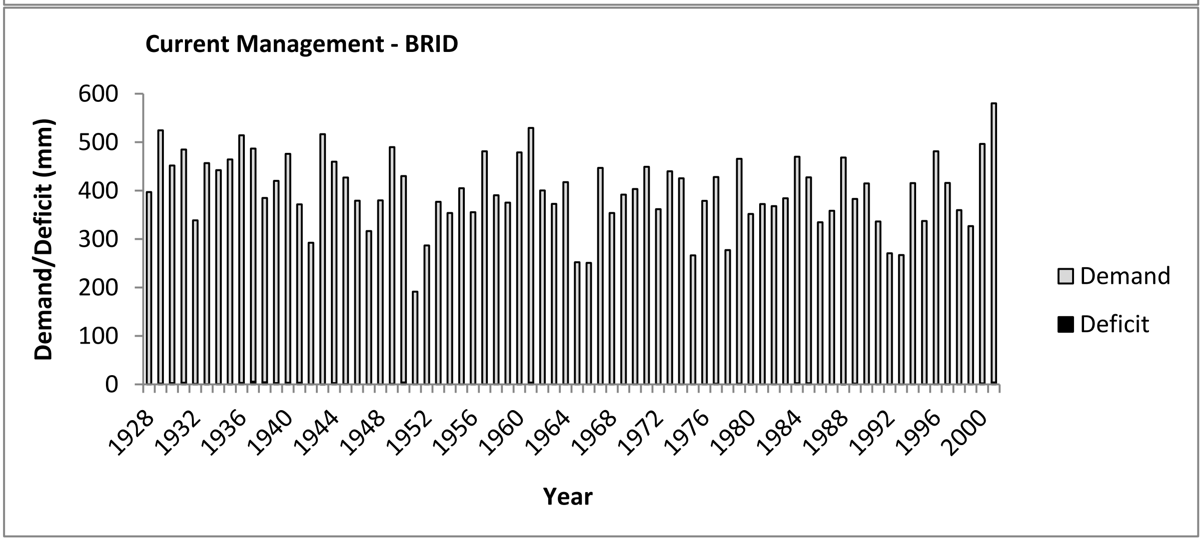
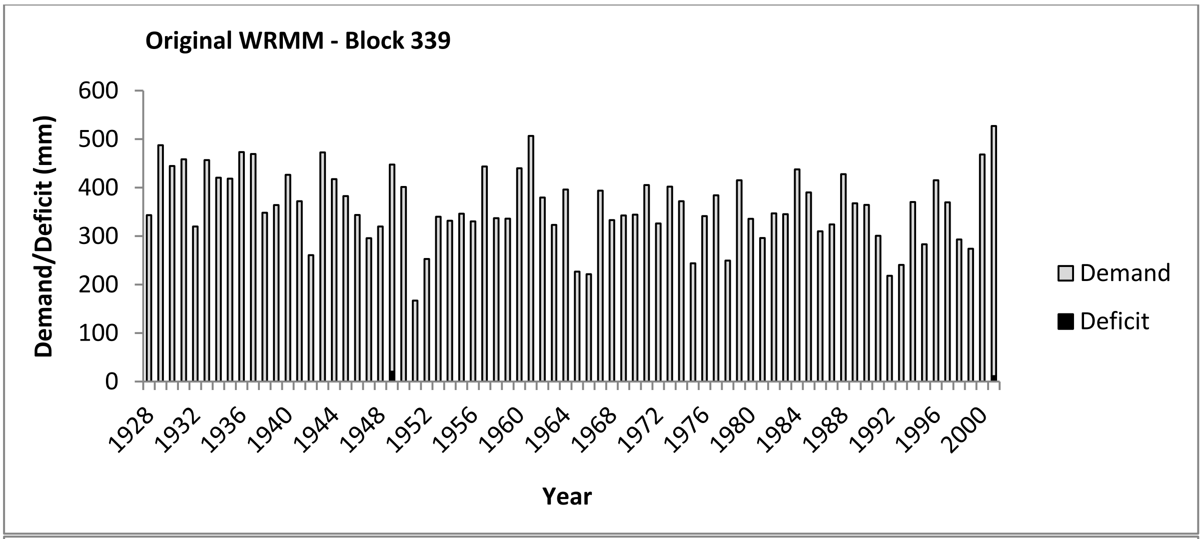
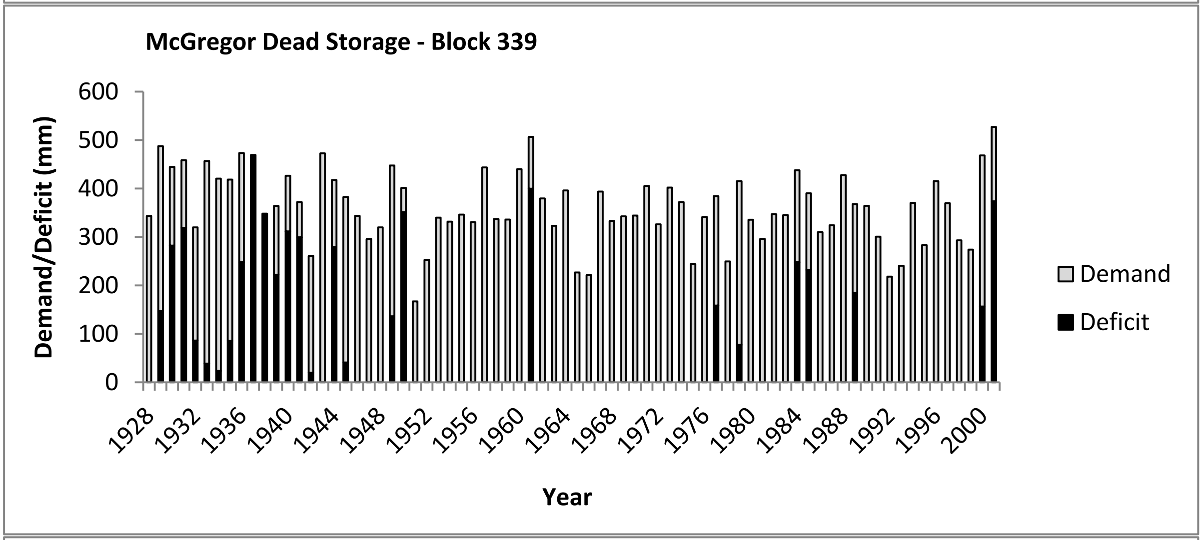


Figure 48: Simulated Area-Weighted Water Deficits for the BRID by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios for the Study Period (1928-2001)





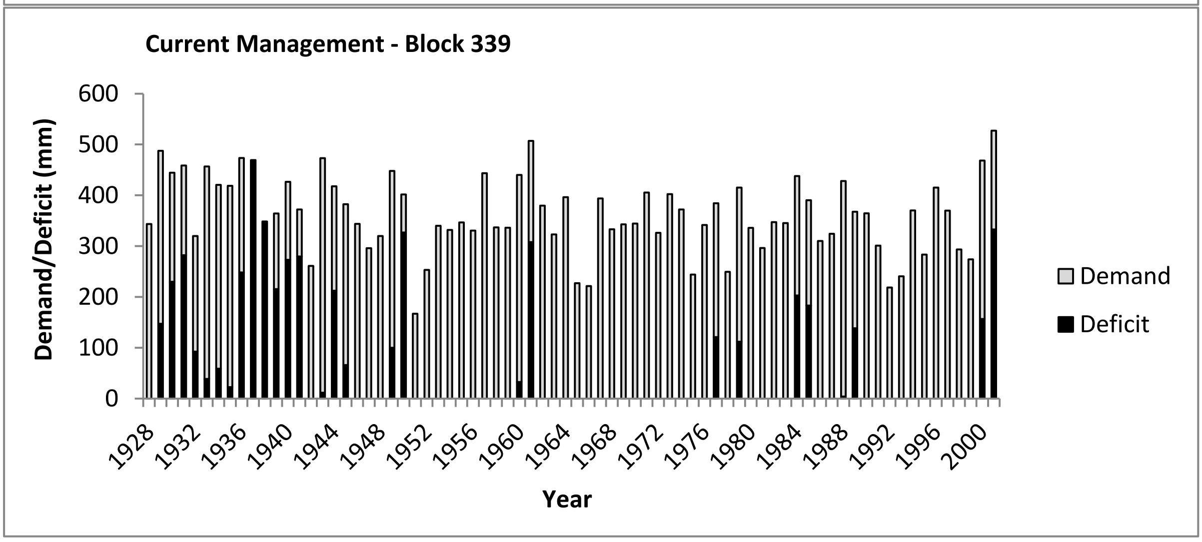


Figure 49: Simulated Water Deficits for the BRID's Block 339 by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios for the Study Period (1928-2001)

5.2.2.3 Typical Dry-Year Water Deficits

The difference in the magnitude of the BRID's deficits simulated in the different scenarios is more noticeable during dry years as shown by the yearly water deficits for two back-to-back dry-year events in Table 24. One of the potential risks of a lower McGregor minimum operating zone was to obtain greater water deficits in the second year of a drought. However, the simulation results show that the total water deficit for the BRID during the second year of two consecutive dry years is reduced between 43 mm (1937) to 100 mm (2001) when McGregor dead storage is included. Indeed, the additional storage that becomes available due to the simulation of McGregor Reservoir's real storage capacity is not fully used during the first dry year. As a result, the available storage remaining can be further depleted to meet the high water demand over a two-year-long drought event. It is particularly beneficial for 2001 as the annual water deficit changes from being above the threshold value of 100 mm when the Original WRMM is used to being more than acceptable as it decreases to about 4 to 5 mm in the alternative scenarios. As the historical dataset did not permit evaluation of the impact of a three-year-long drought, it is possible that more severe water deficits could occur over an extended dry period.

In contrast, the simulation of McGregor's full storage capacity has a slightly negative impact on the water supply for 2000 as the BRID experiences a small area-weighted deficit of 2 millimeters for the McGregor Dead Storage and Current Management scenarios instead of zero deficits as simulated by the Original WRMM. A water deficit of 2 mm is not a problem for irrigation; however, the area-weighted deficit is calculated for the BRID's total area while the simulated deficit is concentrated in the Block 339. As a result, Block 339's deficit is about 157 mm for the McGregor Dead Storage and the Current Management scenarios, which could have severe consequences on the crop yield. Similarly, Block 339 experiences higher water deficits in all the other dry years for the scenarios where McGregor dead storage is simulated. In fact, the magnitude of its annual water deficit could reach up to 469 mm for the year 1937. Similarly to what was observed before, simulating McGregor dead storage is beneficial for all the districts globally but penalizes the irrigators of Block 339.

Figure 50 presents McGregor Reservoir levels for the years 1936 to 1942. The reservoir is drawn down to its lowest operating level in 1937 to meet the high irrigation demand of the two consecutive dry years. However, it took an additional five years to completely recover from the drought and refill McGregor to its ideal level in 1942 in the case of the McGregor Dead Storage and the Current Management scenarios. As a result, Block 339's simulated deficits are above 100 mm for years 1936 to 1941 but all other blocks in the BRID experience no deficit at all. The Original WRMM model could reach higher levels throughout these critical years, but still operates McGregor

Reservoir below its ideal level until 1942. In this case, Block 339 experiences no deficit and the other blocks have acceptable water deficits (below 100 mm) in 1936 and 1937. The successive dry years that took place in the 1930's are referred historically as the dust-bowl period.

Table 24: Water Deficits Simulated for Two Set of Consecutives Dry Years by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios

Irrigation District	1936 Area-Weighted Deficit (mm)				
	Original WRMM	McGregor Dead Storage	Difference with Reference	Current Management	Difference with Reference
WID	174.6	170.9	-3.7	173.9	-0.8
BRID	24.6	3.1	-21.5	3.1	-21.5
EID	81.9	81.9	0.0	81.9	0.0
LNID	192.4	186.3	-6.1	192.8	0.4
Block 339	0.0	248.0	248.0	248.0	248.0
Total	103.2	95.0	-8.2	96.9	-6.2
Irrigation District	**1937 Area-Weighted Deficit (mm)**				
	Original WRMM	**McGregor Dead Storage**	**Difference with Reference**	**Current Management**	**Difference with Reference**
WID	95.5	95.6	0.1	95.6	0.1
BRID	48.4	5.9	-42.6	5.9	-42.6
EID	92.3	92.3	0.0	92.3	0.0
LNID	98.5	97.8	-0.7	97.8	-0.7
Block 339	0.0	469.3	469.3	469.3	469.3
Total	81.5	68.9	-12.6	68.9	-12.6
Irrigation District	**2000 Area-Weighted Deficit (mm)**				
	Original WRMM	**McGregor Dead Storage**	**Difference with Reference**	**Current Management**	**Difference with Reference**
WID	26.9	25.5	-1.5	23.2	-3.7
BRID	0.0	2.0	2.0	2.0	2.0
EID	0.0	0.0	0.0	0.0	0.0
LNID	99.2	99.1	0.0	99.2	0.0
Block 339	0.0	156.6	156.6	156.6	156.6
Total	28.1	28.5	0.4	28.3	0.2
Irrigation District	**2001 Area-Weighted Deficit (mm)**				
	Original WRMM	**McGregor Dead Storage**	**Difference with Reference**	**Current Management**	**Difference with Reference**
WID	153.3	153.3	0.0	153.3	0.0
BRID	105.1	4.7	-100.4	4.1	-100.9
EID	89.1	87.9	-1.2	88.5	-0.6
LNID	297.3	297.3	0.0	297.4	0.0
Block 339	11.4	373.6	362.3	332.6	321.2
Total	153.5	123.9	-29.7	123.9	-29.6

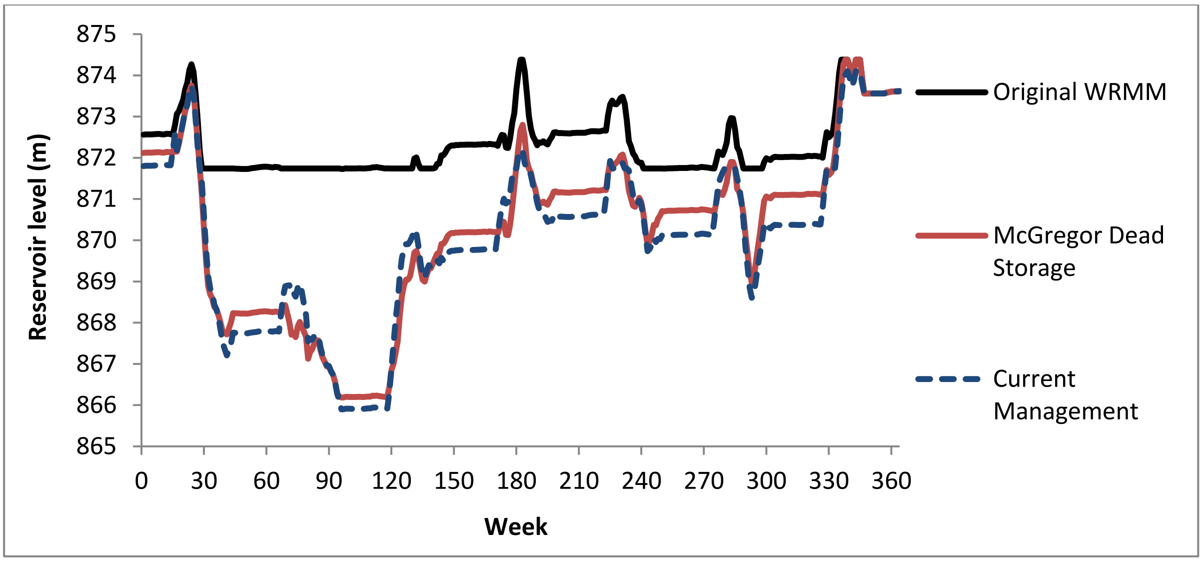


Figure 50: Weekly McGregor Reservoir Levels during the years 1936-1942 (Dust Bowl Period) Simulated by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios

Figure 51 presents simulated McGregor Reservoir levels for the years 2000 and 2001 and the historical McGregor levels as a comparison. McGregor Dead Storage and Current Management scenarios simulated almost the same reservoir levels, but updating the ideal curves still helped to maintain the reservoir slightly higher. Figure 52 shows graphically the weekly demand and deficit values of the Block 339 generated by the three scenarios analysed for the two same dry years (2000-2001). Logically, the Block 339 experiences water deficits as soon as McGregor level goes beyond 871.74 meters; around the week 29 in 2000 and the week 26 in 2001 for the McGregor Dead Storage scenario and around the week 30 in 2000 and 27 in 2001 for the Current Management scenario.

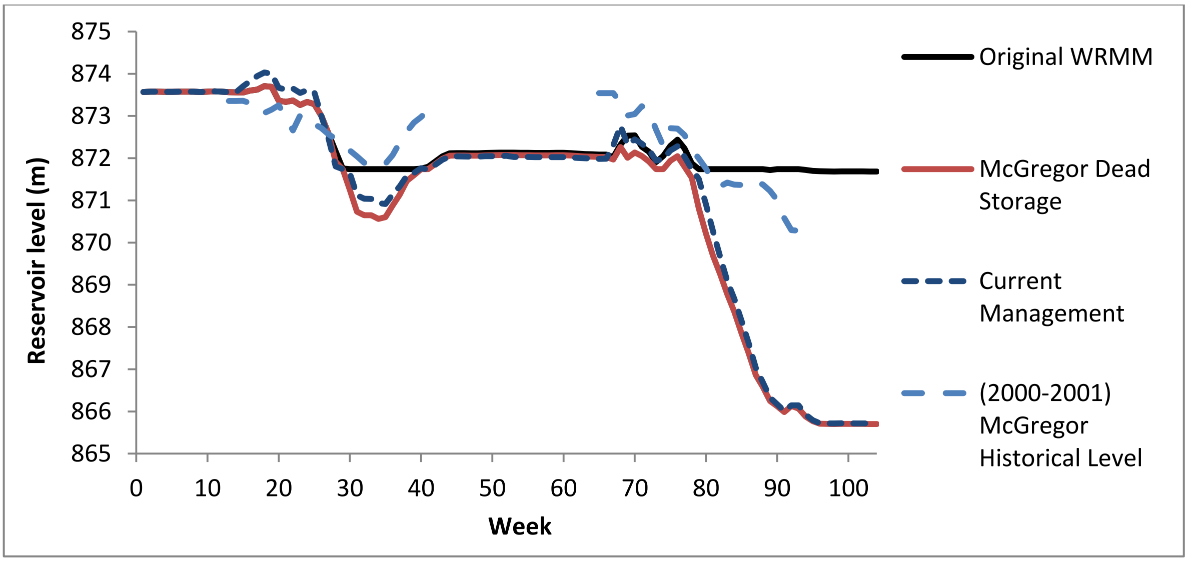


Figure 51: Weekly McGregor Reservoir Levels during Two Consecutives Dry Years (2000-2001) Simulated by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios

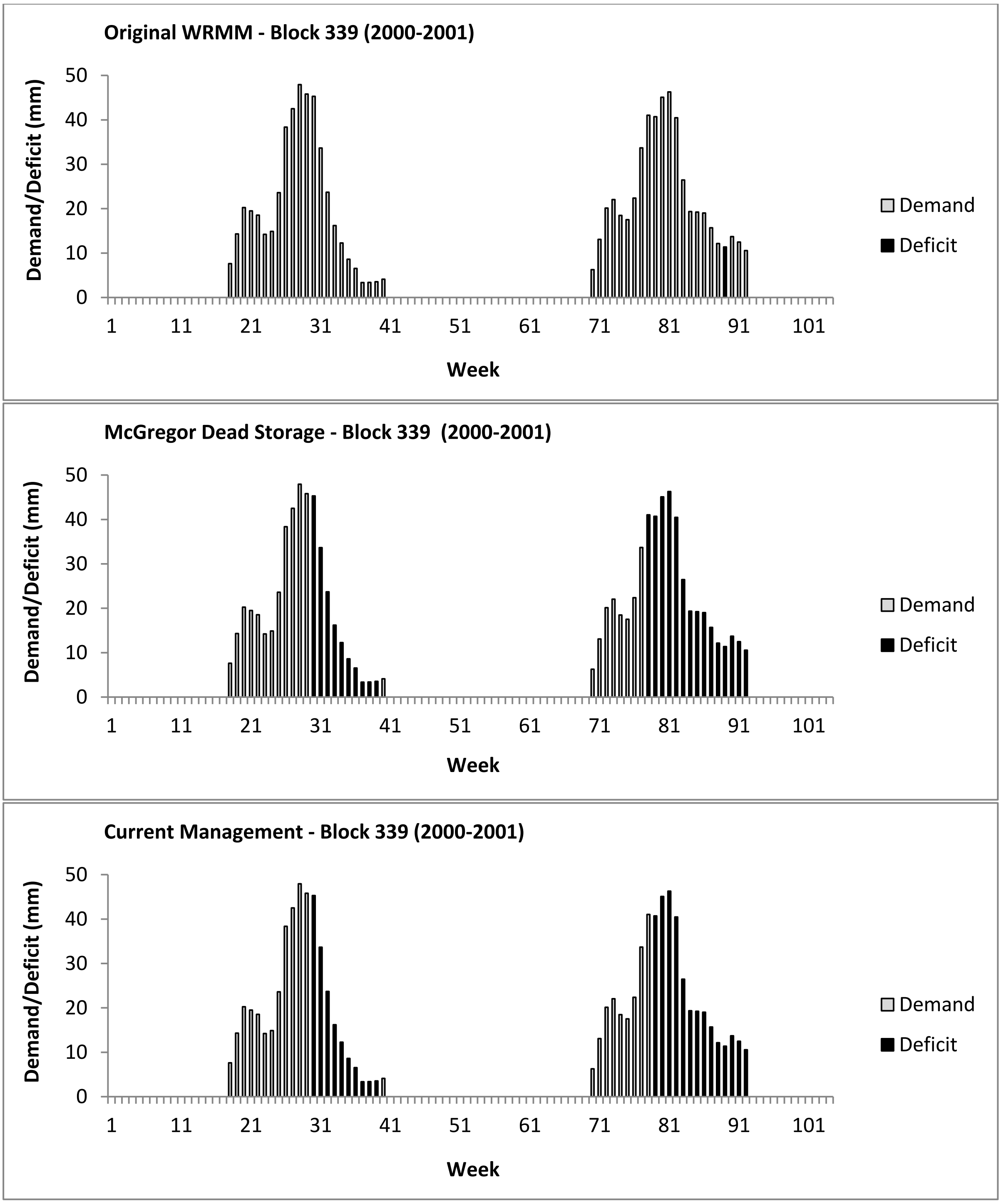


Figure 52: Simulated Weekly Deficits for the Block 339 during the Dry Years 2000-2001 by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios

5.2.2.4 Master Apportionment Agreement Performance

Changing McGregor's minimum operating level decreases the flow delivered at the Saskatchewan border by about 1,400 dam^3 on average for the McGregor Dead Storage scenario and of about 2,150 dam^3 on average for the Current Management scenario. In terms of meeting the Master Apportionment Agreement, the three scenarios did not deliver more than 48% of the natural flow in the drought of 2001. However, the two scenarios representing McGregor real dead storage delivered around 47.5% of the natural flow while the Original WRMM only 47.1%.

5.2.2.5 BRID Diversion Rates

Figure 53 shows the weekly diversion rate of the BRID for the three scenarios analysed. The Original WRMM and the McGregor Dead Storage scenarios produced similar diversion rates in July until the almost the end of August (week 27 to 34); the most critical months for water quality in the Bow River (AESRD 2003). The Current Management scenario generates slightly higher diversion rate in July, August and in the first half of September (week 28 to 37) similarly to what was observed for the Updated Curves scenario. As a result, the Current Management scenario performances are lower in terms of minimizing the diversion rate in the warmest months of the year.

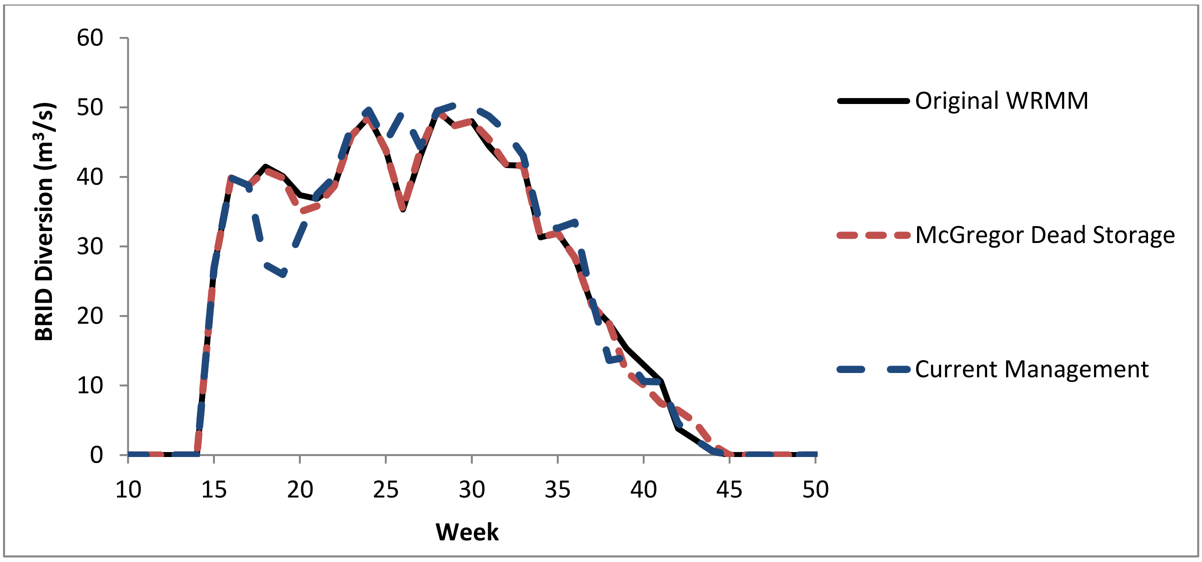


Figure 53: BRID's Average Weekly Diversion Rate in Carseland Canal for Three Typical Normal Years Simulated by the Original WRMM, the McGregor Dead Storage and the Current Management Scenarios

5.2.2.6 BRID's Average Reservoir Levels

Figure 54 shows the BRID's average reservoir levels for the three scenarios assessed as well as the historical data. McGregor simulated levels are closer to the historical data when McGregor lowest operating zone is defined as its dead storage elevation. In the case of the other BRID reservoirs, the McGregor Dead Storage scenario generates average reservoir levels generally similar to the Original WRMM results while the Current Management simulation is comparable to the Updated Ideal Curves simulation presented in the previous section.

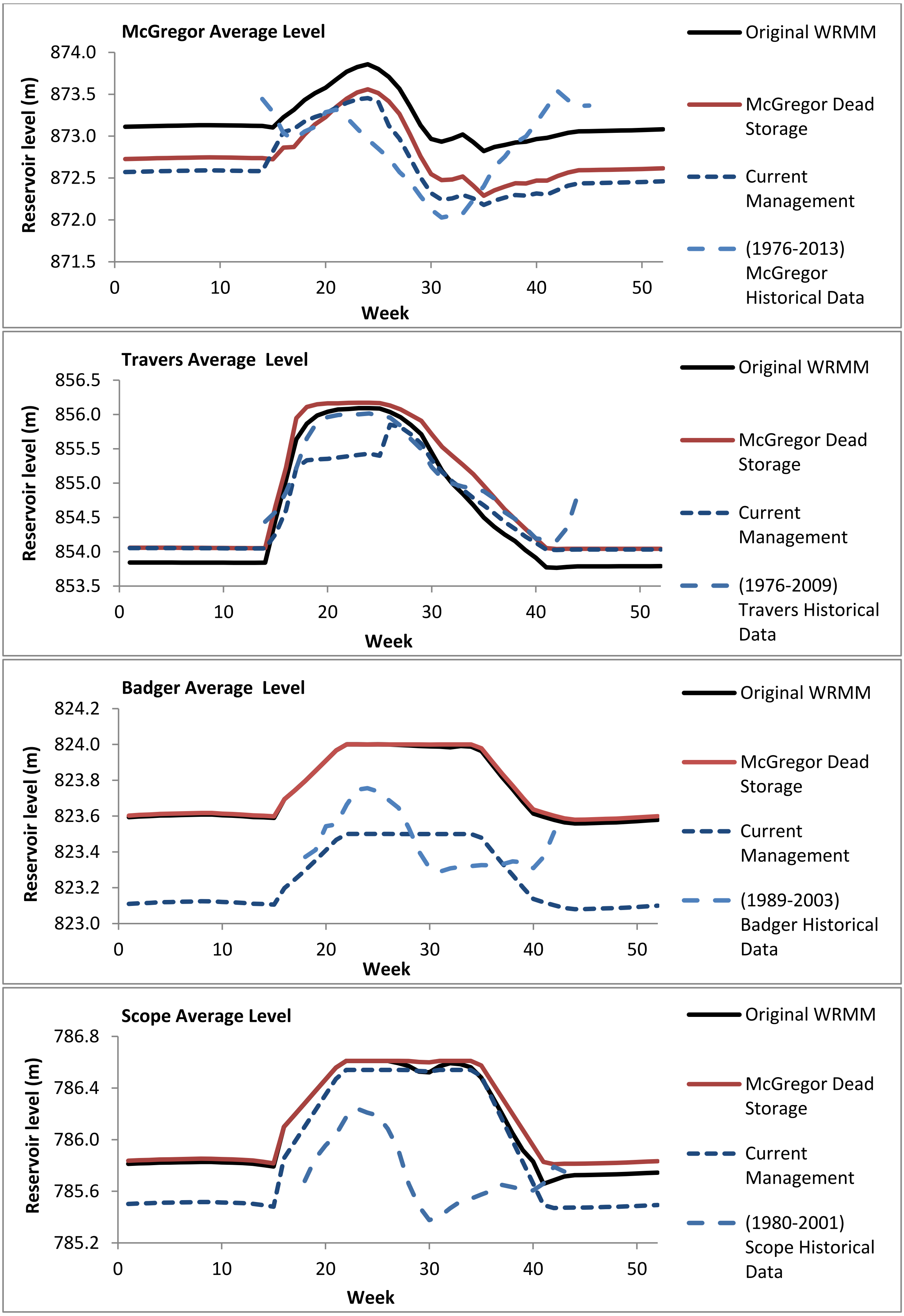


Figure 54: Simulated BRID's Reservoir Average Levels by the Original WRMM, McGregor Dead Storage and the Current Management Scenarios

5.2.2.7 Hypothesis Assessment

The second hypothesis of the reservoir management analysis stated that replacing the McGregor minimum operating zone for its dead storage level in the WRMM model would increase the overall water supply available to meet water demand even if back-to-back dry-year performance could be affected. The hypothesis is validated, because simulating McGregor dead storage is overall beneficial for the irrigation districts even in consecutive dry years. However, Block 339 was considerably penalized, which reduced the gains of lowering McGregor's dead storage level.

The third hypothesis suggested that combining the updated BRID ideal curves and McGregor real dead storage in the WRMM model should improve the modelling results accuracy for irrigation management studies compare to the Original WRMM version. However, even if the results obtained with the Current Management scenario increased the water supply available for irrigation from the Original WRMM, the deficits generated for the Block 339 and the simulated McGregor levels in dry years lead to extreme values. Therefore, the third hypothesis is invalidated. As a result, other parameters such as the penalty setting of the BRID's reservoir operating zones should be reviewed to assess whether improved results could be obtained when McGregor dead storage and the BRID's current operations are simulated. The goal of the following section is to analyse this point.

5.2.3 Inverting the Penalties for Reservoirs in Series

The third objective of the reservoir management section was to assess whether the WRMM performance could be improved by inverting the penalties of the BRID's reservoir operating zones. The fourth hypothesises is:

4. Inverting the BRID's reservoir operating zone penalties in the WRMM model to simulate reservoir management priorities as suggested by the literature would increase the water supply available to meet irrigation demands.

To validate or invalidate the fourth hypothesis, the Original WRMM is compared with the Inverse Penalties scenario and through the comparison of the Current Management scenario with the Current Management – Penalties scenario.

5.2.3.1 Simulated Water Supply

The average water supply simulated by the Original WRMM is compared with the supply obtained from the Inverse Penalties simulation in Table 25. Similarly, Table 26 compares the water supply simulated through the Current Management scenario with the Current Management – Penalties scenario. As shown, inverse penalties tend to provide slightly more water to the BRID, but have the downside of decreasing the water available for the other districts. The difference is generally small: the BRID gains about 0.2 mm when the penalties are inverted while the WID's supply could decrease by 0.6 mm (Current Management – Penalty scenario) to about 1.2 mm (Inverse Penalties scenario). The total area-weighted supply generated for the four districts is globally slightly lower when the penalties are inverted, but the water supply obtained from the Current Management – Penalties is still above the one simulated with the Original WRMM due to McGregor's greater storage.

Table 25 : Simulated Average Water Supply (1928-2001) Available to Meet Irrigation Demand by the Original WRMM and the Inverse Penalties Scenarios

Irrigation District	Original WRMM – Management Reference		Inverse Penalties		Difference with Original
	(mm)	(dam^3)	(mm)	(dam^3)	(mm)
WID	320.6	123,260	319.5	122,817	-1.2
BRID	396.7	417,361	396.8	417,561	0.2
EID	418.6	526,907	418.7	526,956	0.0
LNID	296.9	272,735	296.7	272,539	-0.2
Total	370.9	1,340,263	370.8	1,339,872	-0.1

Table 26 : Simulated Average Water Supply (1928-2001) Available to Meet Irrigation Demand by the Current Management and the Current Management - Penalties Scenarios

Irrigation District	Current Management		Current Management – Penalties		Difference with Current	Difference with Original
	(mm)	(dam^3)	(mm)	(dam^3)	(mm)	(mm)
WID	320.9	123,376	320.3	123,147	-0.6	-0.3
BRID	398.4	419,149	398.5	419,321	0.2	1.9
EID	418.8	527,081	418.7	526,992	-0.1	0.1
LNID	297.0	272,809	296.8	272,650	-0.2	-0.1
Total	371.5	1,342,416	371.4	1 342 110	-0.1	0.5

5.2.3.2 Risk Measures of the Water Deficits

Average values for the water supply available for irrigation do not provide the full picture of the different scenario performance; therefore, the risk measures characterizing the water deficits are also analysed in Table 27 for the Original WRMM and the Inverse Penalties scenarios. Inverting the original set of penalties improves the vulnerability performances for the BRID and the LNID while decreasing the performance of the WID and the EID. However, the reliability or the resilience of the four districts is not impacted.

Table 27 : Risk Measures of the Water Deficits (1928-2001) for the Original WRMM and the Inverse Penalties Scenarios

Irrigation District	Reliability		Resilience		Vulnerability	
	Original WRMM	**Inverse Penalties**	**Original WRMM**	**Inverse Penalties**	**Original WRMM**	**Inverse Penalties**
WID	0.92	0.92	0.91	0.92	35.24	36.27
BRID	0.99	0.99	1.00	1.00	25.92	22.50
EID	0.98	0.98	0.95	0.95	16.75	17.64
LNID	0.88	0.88	0.73	0.71	81.21	80.30
Total	0.95	0.95	0.90	0.90	37.77	36.97

The risk measures of the water deficits for the Current Management and the Current Management – Penalties scenarios are presented in Table 28. The performance of Block 339 has been added to Table 28 as this block is particularly penalized when McGregor dead storage is simulated. Interestingly, when the penalties are inverted in the Current Management scenario, more changes are observable. First of all, the reliability of Block 339 is improved from 0.74 to 0.97. It means that this Block suffers water deficits greater than 100 mm only 3% of the time instead of 26%. Furthermore, the resilience of Block 339 passes from a low 0.53 value to a perfect resiliency value of 1. Indeed, in the Current Management scenario, every time Block 339 had seasonal water deficit greater than 100 mm it lasted for at least two consecutive years about half of the time while under the inverse set of penalties, severe shortages never occur two times in a row. However, its vulnerability is worsened by about 20 mm. Similarly, the BRID's area-weighted vulnerability is also increased when the penalties are inverted. On the district scale, the increase in vulnerability is likely to have practically no consequence, as the BRID's area-weighted deficits are below 100 mm for practically all the simulated years. The performance of the WID and the EID are essentially the same with or without the original set of penalties. The LNID reliability and resilience performances are slightly worsened while its vulnerability is improved.

Table 28 : Risk Measures of the Water Deficits (1928-2001) for the Current Management and the Current Management - Penalties Scenarios

Irrigation District	Reliability		Resilience		Vulnerability	
	Current Management	**Current Management - Penalties**	**Current Management**	**Current Management - Penalties**	**Current Management**	**Current Management - Penalties**
WID	0.92	0.92	0.91	0.92	34.92	34.81
BRID	1.00	1.00	0.99	1.00	1.76	16.96
EID	0.98	0.98	0.95	0.95	16.49	17.23
LNID	0.89	0.88	0.78	0.72	86.54	81.23
Block 339	0.74	0.97	0.53	1.00	141.33	169.04
Total	0.95	0.95	0.91	0.90	31.97	35.29

The increased reliability of the BRID's Block 339 by the inverted set of penalties is shown graphically in Figure 55. Block 339 experiences only two severe seasonal water deficits and never back-to-back high deficits over the length of the study period for the Current Management – Penalties scenario as opposed to about 19 years of high shortages under the original set of penalties modelled in the Current Management scenario.

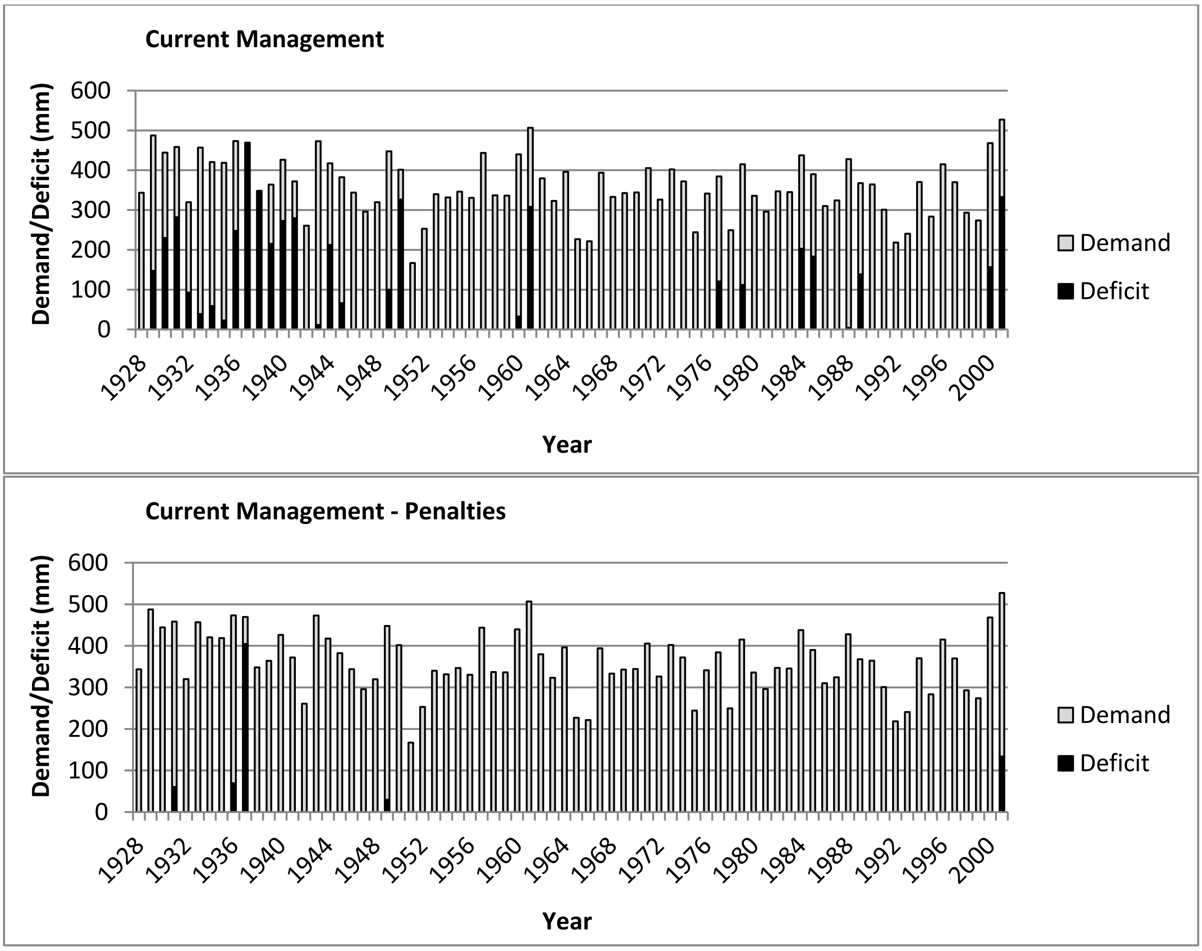


Figure 55: Simulated Water Deficits for the BRID's Block 339 by the Original WRMM, the Inverse Penalties, the Current Management and the Current Management – Penalties scenarios for the study period (1928-2001)

5.2.3.3 Typical Dry Year Water Deficits

The difference in the magnitude of the BRID's water deficits during dry years could be slightly reduced when the penalties are inverted within the Original WRMM as shown by Table 29. Indeed, the difference for three typical dry years varies from 0 mm in 2001 to about 11 mm in 1949. However, these benefits are not particularly noticeable as the 2001's deficit remains above 100 mm. The other districts generally experience higher shortfalls than the BRID in dry years and their water deficits are marginally worsened under the inverted penalties.

Table 29: Simulated Water Deficits for Three Typical Dry Years by the Original WRMM and the Inverse Penalties Scenarios

Irrigation District	1936 Area-Weighted Deficit (mm)			1949 Area-Weighted Deficit (mm)			2001 Area-Weighted Deficit (mm)		
	Original WRMM	Inverse Penalties	Diff. with Reference	Original WRMM	Inverse Penalties	Diff. with Reference	Original WRMM	Inverse Penalties	Diff. with Reference
WID	174.6	174.6	0.0	113.4	116.8	3.3	153.3	153.3	0.0
BRID	24.6	21.3	-3.2	10.6	0.0	-10.6	105.1	105.1	0.0
EID	81.9	82.1	0.2	39.7	41.0	1.3	89.1	90.3	1.2
LNID	192.4	192.8	0.4	60.1	60.1	0.0	297.3	299.6	2.2
Total	103.2	102.4	-0.8	44.3	42.0	-2.3	153.5	154.5	1.0

The difference in the magnitude of water deficits occurring in consecutive dry years was compared for the Current Management scenario and the Current Management – Penalties scenario as presented in Table 30. Again, it could be notice that inverting the penalties for the BRID's reservoir system does not impact the Original WRMM performance much but particularly improves the performance of the Current Management scenario. In this case, inverting the penalties produces smaller deficits for the BRID and particularly for Block 339. Indeed, because a highest priority is associated to McGregor reservoir, its level is maintained closer to the ideal level, which diminishes the diversion cut off for Block 339. The benefits for the irrigators of this block are manifested in the simulated years 1936 and 2000. Indeed, the severe water shortages are reduced to more acceptable levels: 69 mm in 1936 and only 4 mm in 2000. The water deficits occurring in the second year of two back-to-back dry years (1937 and 2001) still remain above the threshold of 100 mm. In the year 1937, the BRID's total water deficit increases from about 6 mm to 46 mm; still an acceptable value. Similarly to what was observed before, inverting the penalties has the downside of slightly increasing the shortfall in water for the other districts. However the difference is small enough that the relative water deficit severity remains unchanged for the other districts. Globally, the Current Management – Penalties scenario produces lower water deficits than the Original WRMM scenario in dry years and the gains are mainly beneficial for the BRID.

Table 30: Simulated Water Deficits for Two Set of Consecutives Dry Years by the Original WRMM, the Current Management and the Current Management – Penalties Scenarios

Irrigation District	1936 Area-Weighted Deficit (mm)				
	Original WRMM	Current Management	Current Management – Penalties	Difference with Current	Difference with Reference
WID	174.6	173.9	174.8	0.9	0.1
BRID	24.6	3.1	2.4	-0.7	-22.2
EID	81.9	81.9	82.1	0.2	0.2
LNID	192.4	192.8	192.8	0.0	0.4
Block 339	0.0	248.0	69.4	-178.6	69.4
Total	103.2	96.9	96.9	0.0	-6.3

Irrigation District	1937 Area-Weighted Deficit (mm)				
	Original WRMM	Current Management	Current Management – Penalties	Difference with Current	Difference with Reference
WID	95.5	95.6	95.6	0.0	0.1
BRID	48.4	5.9	45.6	39.8	-2.8
EID	92.3	92.3	93.4	1.1	1.1
LNID	98.5	97.8	98.4	0.6	-0.1
Block 339	0.0	469.3	404.5	-64.8	404.5
Total	81.5	68.9	81.0	12.1	-0.5

Irrigation District	2000 Area-Weighted Deficit (mm)				
	Original WRMM	Current Management	Current Management – Penalties	Difference with Current	Difference with Reference
WID	26.9	23.2	26.9	3.7	0.0
BRID	0.0	2.0	0.0	-2.0	0.0
EID	0.0	0.0	0.0	0.0	0.0
LNID	99.2	99.2	102.8	3.6	3.6
Block 339	0.0	156.6	0.0	-156.6	4.1
Total	28.1	28.3	29.0	0.7	0.9

Irrigation District	2001 Area-Weighted Deficit (mm)				
	Original WRMM	Current Management	Current Management – Penalties	Difference with Current	Difference with Reference
WID	153.3	153.3	153.3	0.0	0.0
BRID	105.1	4.1	1.7	-2.5	-103.4
EID	89.1	88.5	87.2	-1.2	-1.9
LNID	297.3	297.4	297.3	0.0	0.0
Block 339	11.4	332.6	133.6	-199.0	122.2
Total	153.5	123.9	122.8	-1.2	-30.8

Figure 56 presents McGregor Reservoir levels for the years 1936 to 1942 for the four scenarios analysed. In the case of the Original WRMM, inverting the penalties of the BRID reservoir system permits the refilling of McGregor Reservoir to its ideal level sooner. Indeed, McGregor reaches its ideal level in 1938 as opposed to 1942. Similarly, McGregor levels remain higher under the Current Management – Penalties scenario compare to the Current Management scenario. McGregor Reservoir is drawn down below the elevation at which irrigators experience pumping difficulties only for the years 1936 and 1937 as opposed to the full 1936-1942 period.

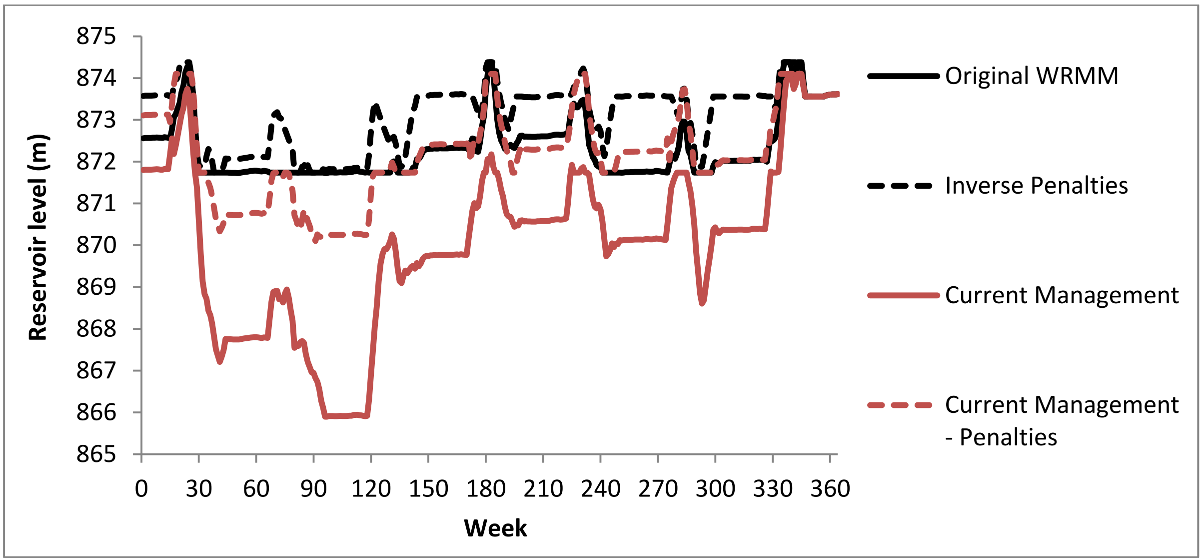


Figure 56: Simulated Weekly McGregor Levels during the years 1936-1942 (End of the Dust Bowl Period) by the Original WRMM, Inverse Penalties, Current Management and the Current Management – Penalties Scenarios

Figure 57 and Figure 58 show graphically the weekly area-weighted deficits of the BRID's blocks and the weekly deficits of Block 339 alone for the 1936 to 1938 period. Only the Original WRMM, the Current Management and the Current Management - Penalties scenarios are compared as the Inverse Penalty simulated water deficits are similar to the Original WRMM. As shown by Figure 57, the water deficits occurring in the BRID during the year 1937 are mostly concentrated in week 80. In contrast, the Current Management – Penalties simulates deficits more distributed over the season and of smaller magnitudes between the weeks 77 to 82, which should be less damaging for crop yields. The Current Management scenario simulates no overall deficit for the BRID. However, this scenario generates the highest deficits for Block 339 as depicted by Figure 58. More particularly, this block is unable to divert water for the entire irrigation seasons of 1937 and 1938 and suffers large water deficits in 1936. When the penalties are inverted, this block experiences only small deficits in the year 1936 and 1938, which could minimize the economic impact of having a severe shortage of water in 1937.

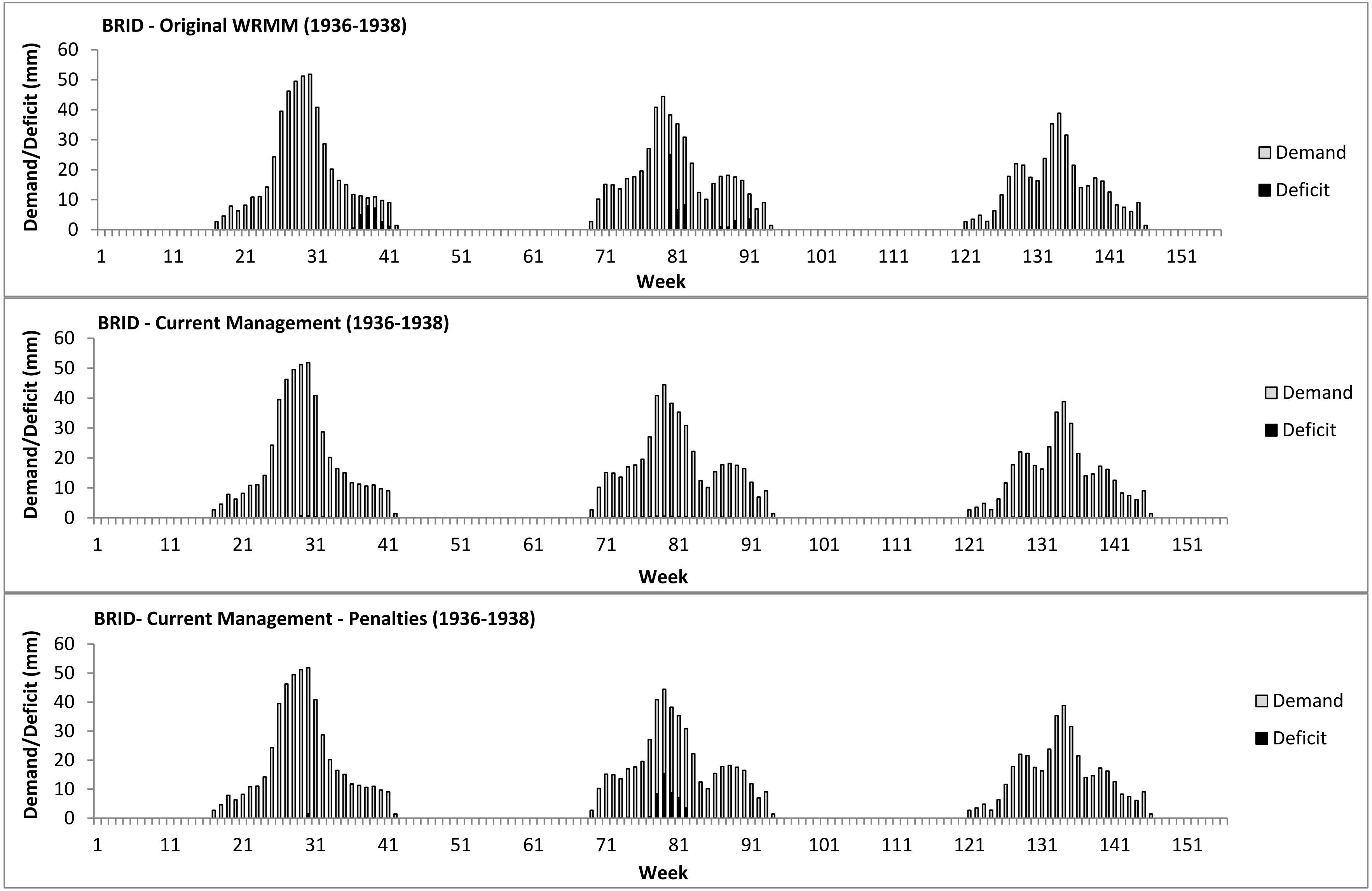


Figure 57: Simulated Weekly Area-Weighted Deficits for the BRID (1936-1938) by the Original WRMM, the Current Management and the Current Management – Penalties Scenarios

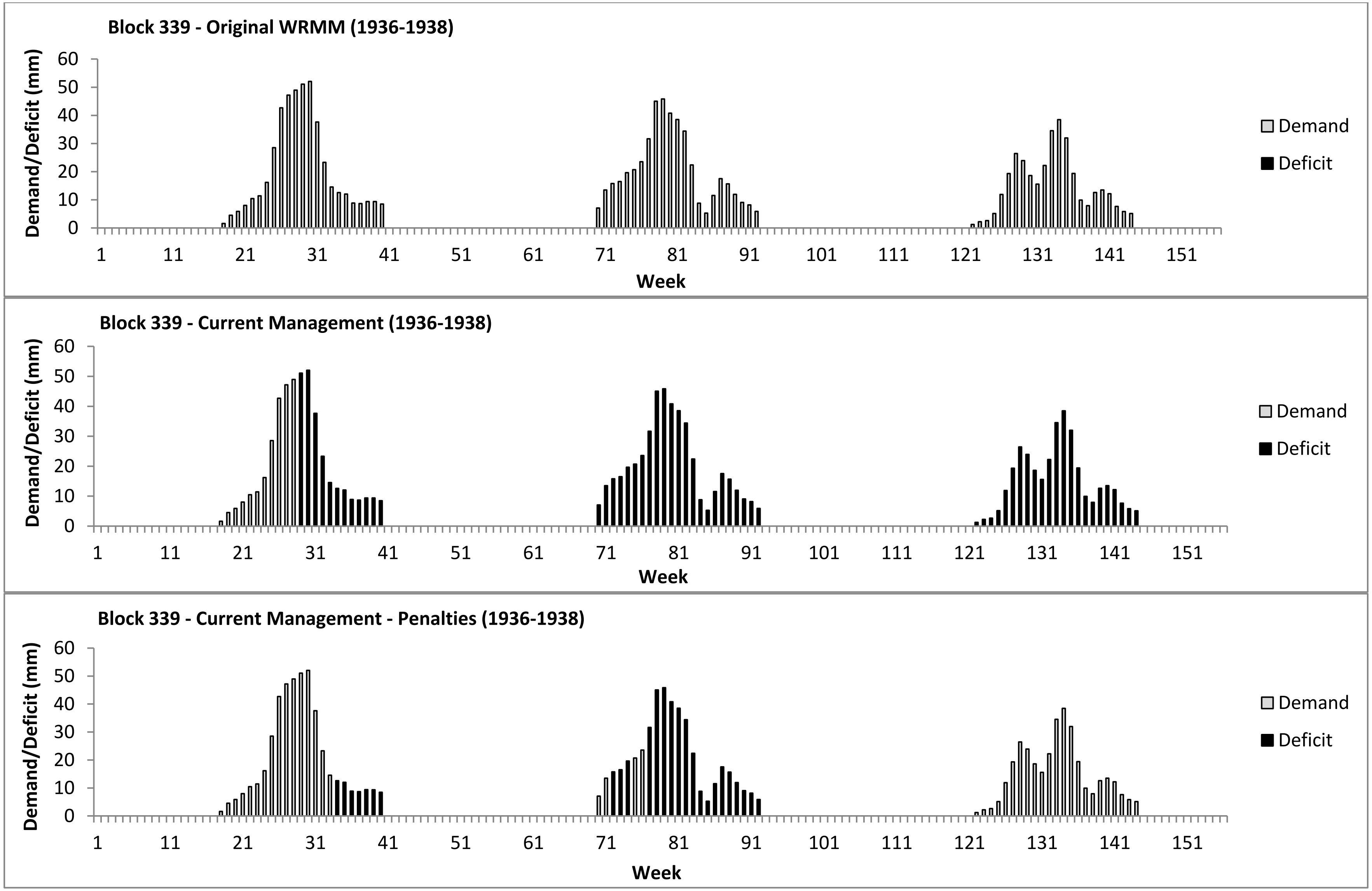


Figure 58: Simulated Weekly Deficits for the BRID's Block 339 (1936-1938) by the Original WRMM, the Current Management and the Current Management – Penalties Scenarios

Figure 59 presents McGregor Reservoir levels for the years 2000 and 2001 as simulated by the four scenarios and the historical levels. The Inverse Penalties generated reservoir levels that are closer to the historical ones for the second half of 2000 and the year of 2001. Indeed, the winter levels reached historically are the same as the one simulated for this scenario. Moreover, inverting the penalties of the Current Management scenario permitted a less severe draw down of McGregor Reservoir in 2001 compared with the values obtained under the original set of penalties. However, the reservoir is still depleted much lower than what occurred historically.

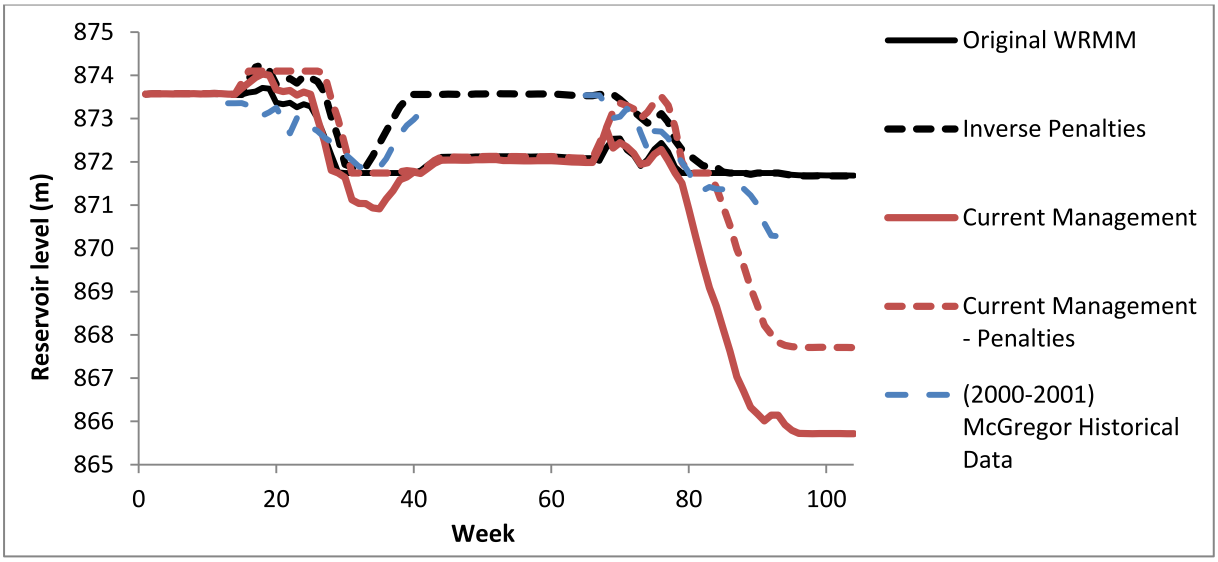


Figure 59: Simulated Weekly McGregor Levels during Two Consecutives Dry Years (2000-2001) by the Original WRMM, the Inverse Penalties, the Current Management and the Current Management – Penalties WRMM Scenarios

5.2.3.4 Master Apportionment Agreement Performance

Regarding the Master Apportionment Agreement performance, inverting the penalties increases on average the flow passing the Saskatchewan border by about 560 dam^3 compared with the Original WRMM version. However, it reduced slightly the flow in the year 1937 compare with the original case. Indeed, under the inverse set of penalties the flow falls below the 50% value, but the difference is small enough that it is not considered critical: 49.89%. Similarly, inverting the penalty of the Current Management scenario increases the flow by about 950 cubic decametres compared to the Current Management scenario, which is using the original set of penalties. In this case, even the year 1937 meets the Master Apportionment Agreement. The natural flow delivered in the drought of 2001 still lies below the threshold value of 48% for all the scenarios analysed. For the Inverse Penalty scenario the flow decreases to 47.09% compare to 47.12% delivered by the Original WRMM. In the case of the Current Management – Penalty scenario the flow is reduced to 47.52% instead of

47.55% as simulated by the Current Management scenario. Therefore, in both cases inverting the penalties reduced slightly the flow delivered to meet the Master Apportionment Agreement.

5.2.3.5 BRID's Diversion Rates

Figure 60 shows the weekly diversion rate for the BRID for the four scenarios analysed. In both cases, inverting the penalties increases slightly the diversion rate in July until mid-August (week 28 to 33), which is less beneficial for the Bow River water quality. On the other hand, the Inverse Penalty scenario generates lower diversion rates during the month of September (week 35 to 39) compared with the Original WRMM but it is not the case under Current Management – Penalties scenario.

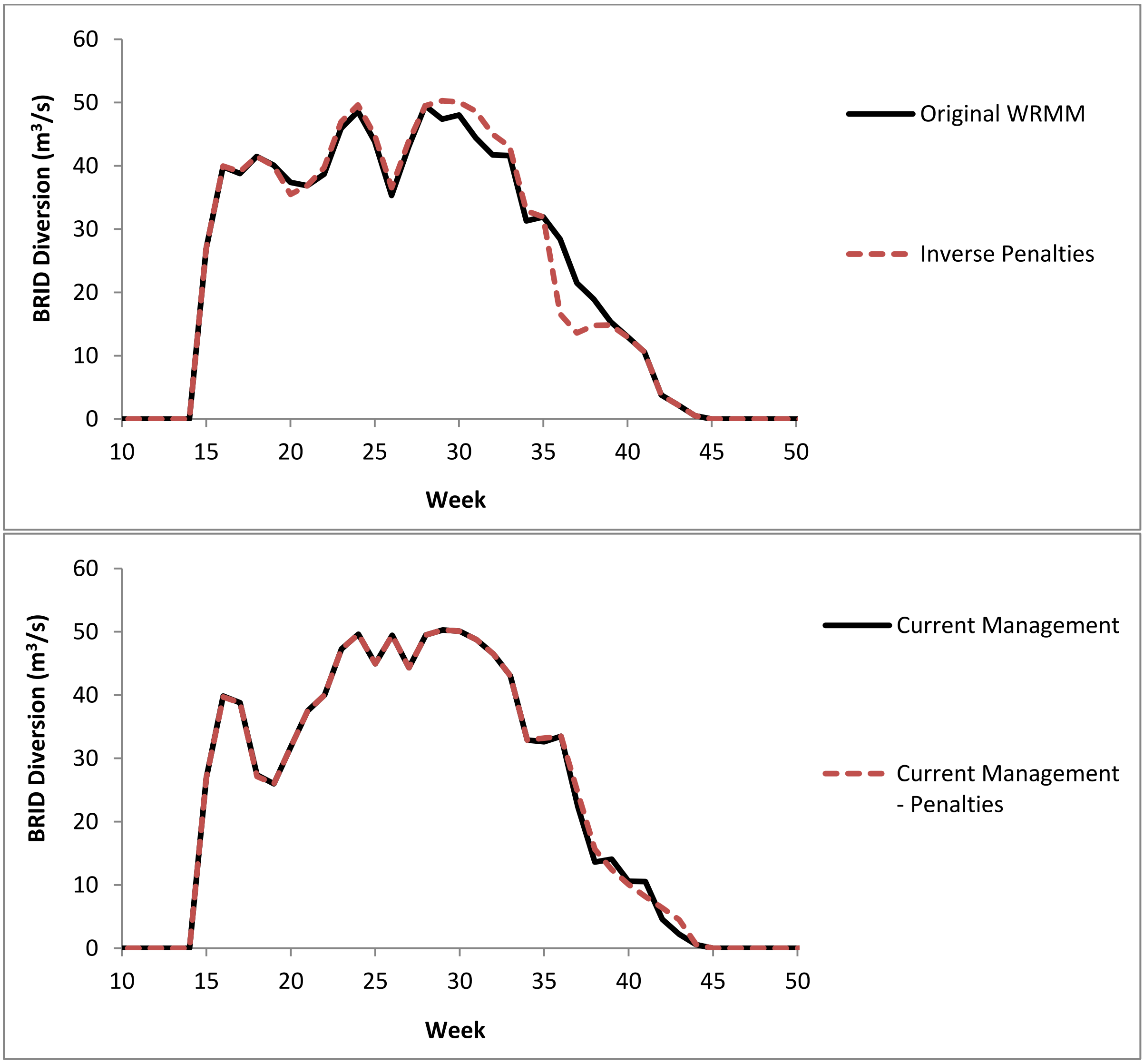


Figure 60: BRID's Average Weekly Diversion Rate in Carseland Canal for Three Typical Normal Years Simulated by the Original WRMM, the Inverse Penalties, the Current Management and the Current Management – Penalties Scenarios

5.2.3.6 BRID's Average Reservoir Levels

Figure 61 and Figure 62 compare the average reservoir levels for the BRID obtained from the normal set of penalties and with the inverted penalties setting for the Original WRMM and the Current Management version as well as the historical average levels. It is interesting to note that Badger's and Scope's simulated levels are much closer to the historical data under the inverted penalties. In contrast, the Current Management scenario produced more realistic levels for McGregor and Travers-Little Bow reservoirs under the original set of penalties. Inverting the penalties produced on average lower reservoir levels for Travers-Little Bow, Badger and Scope and a higher average level was reached for McGregor. Indeed, as the highest penalties are allocated to McGregor, this reservoir is maintained closer to its ideal curve. When the original set of penalties is used, the ideal curves of Badger and Scope are prioritized by the model and as a result, their levels remain unrealistically constant. Therefore, it seems that the levels of reservoirs having lower relative penalties tend to fluctuate more, which lead to more realistic results than the reservoir levels conditioned by higher relative penalties, which are maintained more strictly close to the ideal rule curves.

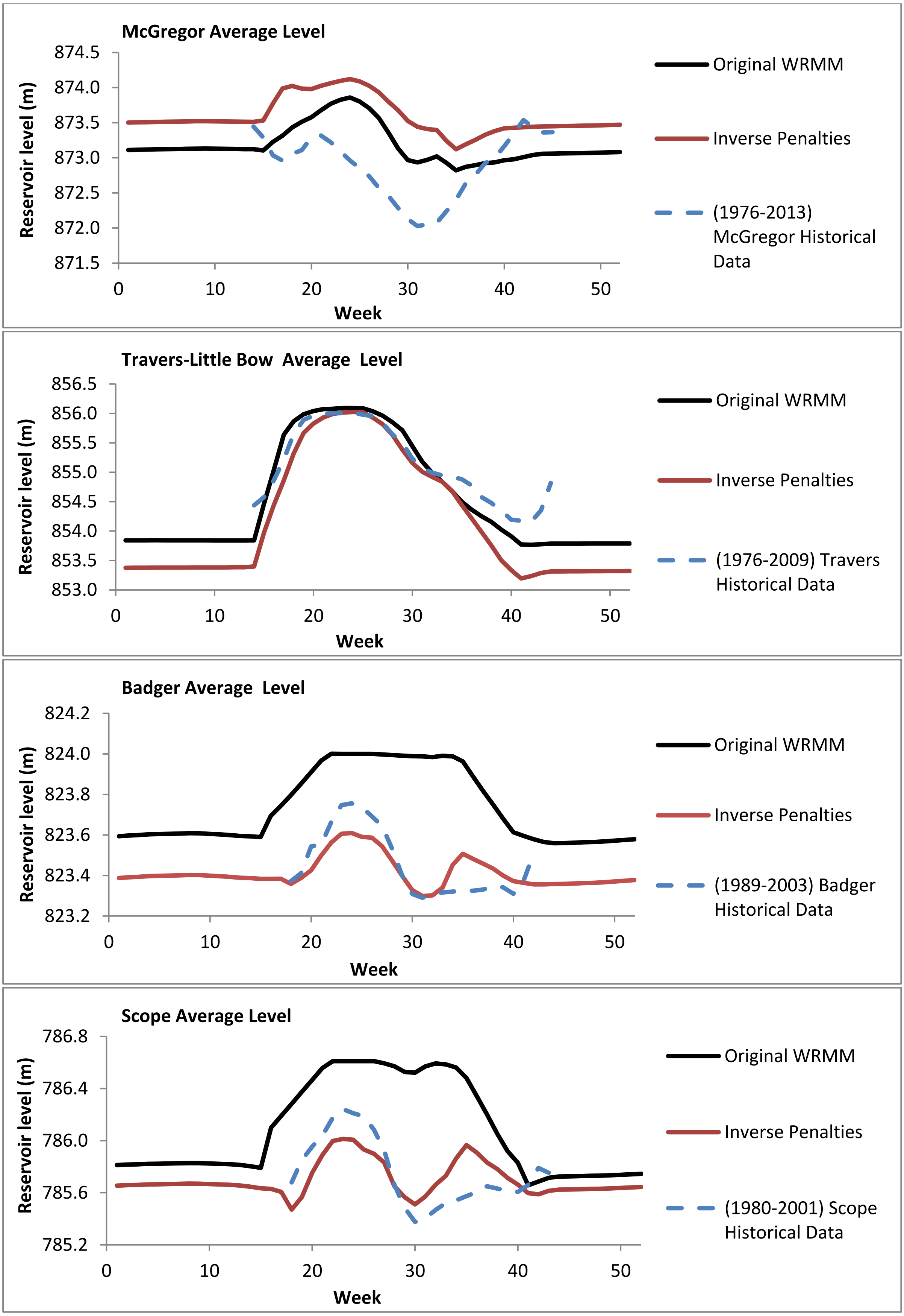


Figure 61: Simulated BRID's Reservoir Average Levels by the Original WRMM and Inverse Penalties Scenarios

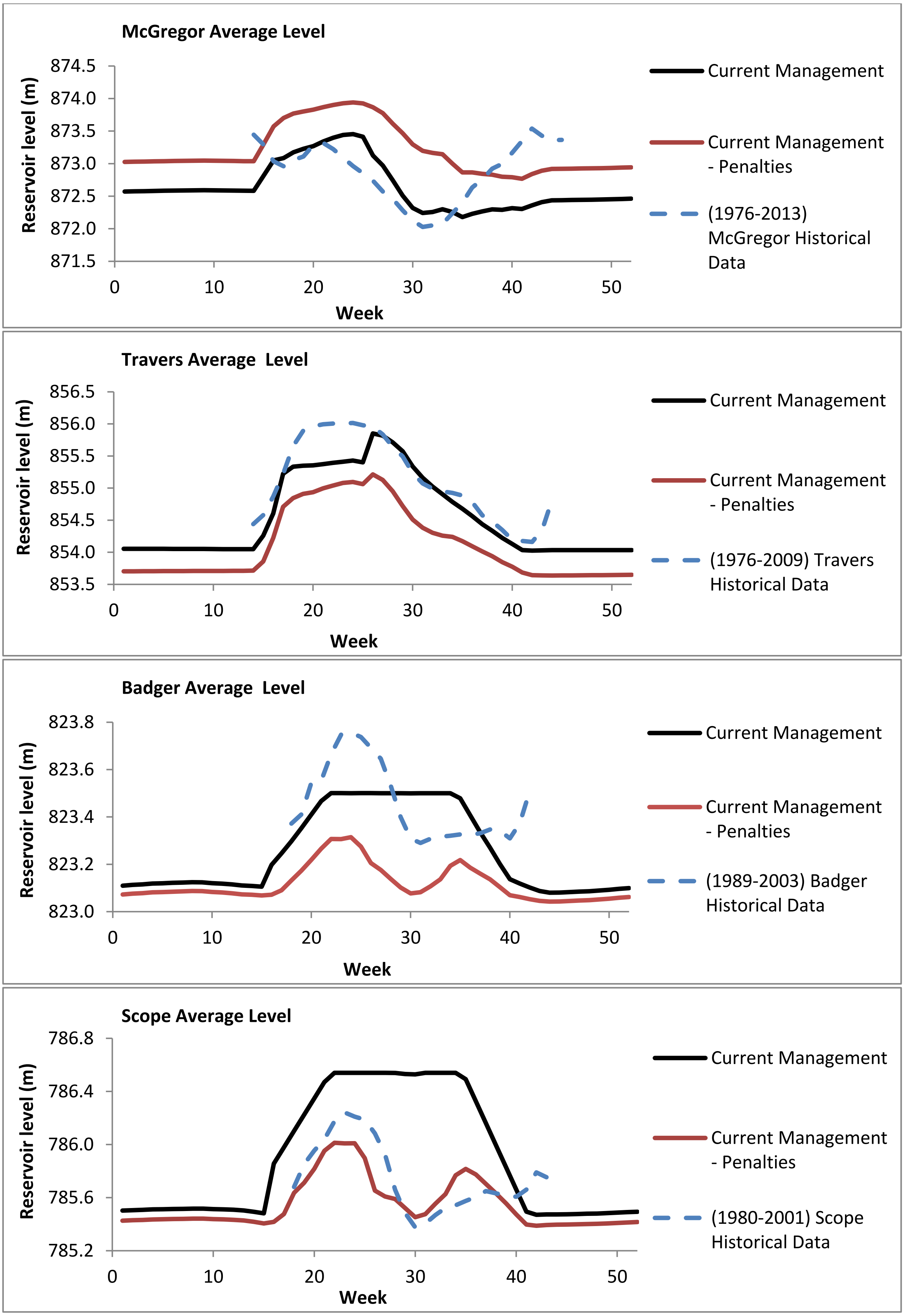


Figure 62: Simulated BRID's Reservoir Average Levels by the Current Management and Current Management – Penalties Scenarios

Figure 63 presents Badger and Scope reservoir levels for the three typical dry years of the study period obtained from the Original WRMM model. During dry conditions these reservoirs are drawn down below their minimum operating levels, which are respectively 823.00 meters and 785.31 meters, but the penalty for the lowest operating zone of these reservoirs is only 1190. As indicated in the Methodology section, the penalty associated with the BRID's reservoirs minimum operating zone has been increased to 10,000 in the Inverse Penalties and Current Management – Penalties models in order to maintain the BRID's internal reservoirs above their respective minimum operating level, which is more realistic.

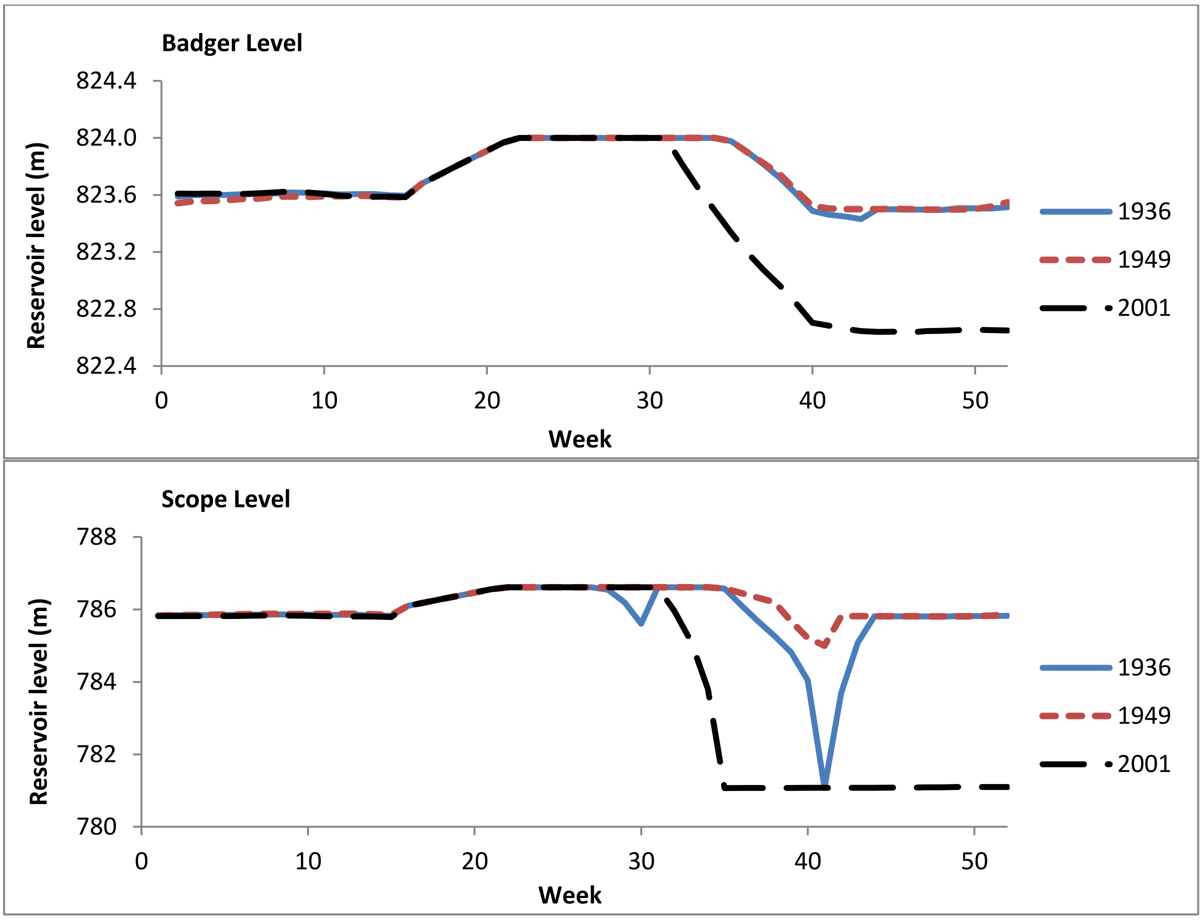


Figure 63: Simulated BRID's Internal Reservoirs Levels during Three Typical Dry Years by the Original WRMM

5.2.3.7 Assessment of the Hypotheses

It was believed that inverting the penalties of the BRID's reservoir operating zones in the Original WRMM model and in the Current Management scenario would increase the water supply available to meet water demand. The simulation results show that the BRID's average water deficits were indeed reduced and validated the hypothesis. However, the other districts' average deficits were increased slightly. Similarly, the scenario performances in terms of the risk measures of the water deficits were improved for the BRID under the inverted set of penalties and could sometimes penalize the other districts, to a small extent. More particularly, the Current Management – Penalties scenario produced better results for the BRID compared to the Current Management scenario as McGregor reservoir was maintained higher, which minimized the diversion cut off for Block 339. Moreover, this scenario simulated lower water deficits in dry years compared to the Original WRMM at a district scale. Block 339 experienced the most negative impact with the Current Management scenario rather than Current Management – Penalties, but the Original WRMM still simulated the lowest deficits for this specific block. Finally, no real benefits were noted for the Master Apportionment Agreement and the diversion rate in normal years by inverting the penalties.

On the other hand, the penalty scheme used in any version of the WRMM tends to reduce storage level fluctuations for the reservoirs for which higher penalties are assigned. As a result, the historical flexibility in reservoir operations is poorly captured by the model simulations, even if the penalties are inverted.

Moreover, even if the best performances for the BRID were generated under the Current Management – Penalties simulation, the overall performance of both the Original WRMM and the Current Management – Penalties scenarios were similar according to the criteria normally used by AAF. Indeed, a scenario is considered acceptable for planning irrigation management if water deficits above or equal to 100 mm occur in less than 10% of the years simulated. It was found that all scenarios produced similar reliability values; therefore, using one or the other version of the WRMM would lead to similar conclusions in terms of evaluating the risks for irrigation. All districts proved to have acceptable reliability except the LNID, which experienced shortages higher than 100 mm for about 11 to 12% of the time (reliability of 0.88 to 0.89) for the high irrigation demand simulated. Based on this this analysis, it is recommended that results simulated under both versions, the Original WRMM and the Current Management – Penalties version, be assessed when evaluating irrigation risks for planning studies.

5.2.4 Simulation of Drought Mitigation Curves

The fourth objective of the reservoir management analysis was to assess the benefits of managing the BRID's external reservoirs, McGregor and Travers-Little Bow, exclusively to mitigate drought impacts as opposed to serving multi-purpose water-uses. The fifth hypothesis is therefore as follows:

5. Simulating reservoir operations in the WRMM model as if the BRID's external reservoirs would serve solely drought-mitigation purposes would increase the water supply available to meet irrigation demand and other water-uses in the Bow River Basin.

To validate or invalidate the fifth hypothesis, the Current Management – Penalties scenario is compared with the Drought Mitigation Curves – Penalties scenario. The Current Management – Penalties scenario was used as the reference scenario to assess this hypothesis as it represents most closely the current BRID's operations and generated the most optimal results for this district.

5.2.4.1 Simulated Water Supply

The average water supply simulated by the two scenarios analysed is compared in Table 31. In accordance with expectations, the Drought Mitigation – Penalties scenario does provide a higher average water supply for the BRID of about 0.2 mm. Moreover, the water supply allocated to the other districts is also slightly improved. Overall, the average area-weighted supply obtained for the four irrigation districts from the Drought Mitigation – Penalties scenario is above the one simulated by the Current Management – Penalties scenario and by the Original WRMM.

Table 31 : Simulated Average Water Supply (1928-2001) Available to Meet Irrigation Demand by the Current Management-Penalty and the Drought Mitigation - Penalties Scenarios

Irrigation District	Current Management – Penalties		Drought Mitigation – Penalties		Difference with Current	Difference with Original
	(mm)	(dam^3)	(mm)	(dam^3)	(mm)	(mm)
WID	320.3	123,147	320.7	123,308	0.4	0.1
BRID	398.5	419,321	398.7	419,538	0.2	2.1
EID	418.7	526,992	418.8	527,056	0.1	0.1
LNID	296.8	272,650	297.0	272,821	0.2	0.0
Total	371.4	1,342,110	371.5	1,342,723	0.2	0.7

5.2.4.2 Risk Measures of the Water Deficits

The risk measures of the water deficits for the Current Management – Penalties and the Drought Mitigation – Penalties scenarios are presented in Table 32. In this case also, the Drought Mitigation – Penalties scenario provided slightly better performance than the Current Management – Penalties scenario. Indeed, operating the BRID's external reservoirs using drought mitigation curves decreases the BRID vulnerability approximately by half. The benefits are particularly noticeable for Block 339, whose vulnerability changes from 169 mm to about 95 mm while conserving the same reliability and resiliency. The other districts' results are less affected by the new curves being modelled: the WID's vulnerability is worsened by about 2 mm but its reliability is slightly increased while EID's vulnerability is improved by about 2.5 mm and its reliability is marginally decreased. The four districts' total area-weighted performances are the same for the reliability and resiliency but the total vulnerability is improved under the Drought Mitigation – Penalties scenario.

Table 32 : Risk Measures of the Water Deficits (1928-2001) for the Current Management and the Current Management - Penalties Scenarios

Irrigation District	Reliability		Resilience		Vulnerability	
	Current Management - Penalties	Drought Mitigation - Penalties	Current Management - Penalties	Drought Mitigation - Penalties	Current Management - Penalties	Drought Mitigation - Penalties
WID	0.92	0.93	0.92	0.92	34.81	36.91
BRID	1.00	1.00	1.00	1.00	16.96	8.73
EID	0.98	0.97	0.95	0.95	17.23	14.75
LNID	0.88	0.88	0.72	0.72	81.23	79.60
Block 339	0.97	0.97	1.00	1.00	169.04	95.05
Total	0.95	0.95	0.90	0.90	35.29	31.86

5.2.4.3 Typical Dry Year Water Deficits

The difference in the magnitude of deficits occurring in consecutive dry years was also compared for both scenarios and is presented in Table 33. The scenario performances are improved when the rule curves of the BRID's external reservoirs are changed to mitigate drought impact. Indeed, the dry year shortages simulated by the Drought Mitigation – Penalties scenario are decreased compared to the results simulated by the Current Management – Penalties scenario. More particularly, the Drought Mitigation – Penalties simulations can reduce Block 339 shortages by as much as 129 mm and the overall BRID's shortage by 15 mm in 1937. The WID's water deficit can also be reduced by about 5 mm in 2000. In fact, all the districts except the LNID benefit to a small extent with the new ideal curves modelled in the Drought Mitigation – Penalties scenario compared to the Current Management – Penalties scenario during the two back-to-back dry-year events. The LNID performance remains the same under both scenarios.

The results obtained in dry years could be explained by the higher rule curves simulated for the BRID's external reservoirs in the Drought Mitigation – Penalties scenario. Indeed, as the reservoirs are maintained higher, more water becomes available to meet the irrigation demand of the BRID through district's storage. Moreover, the BRID diversions at the beginning of the season are generally reduced as the higher winter levels provide already some of the water necessary to refill the district reservoirs. As a result, the WID also benefits from the BRID additional storage as the higher river stage at the beginning of the season permits the WID to increase its diversion during the first year of a dry period, such as in 1936 or 2000. However, during the second year of a drought, the BRID needs to divert more water to refill its external reservoirs, which explains why the WID's water deficits are not improved in 1937 or 2001.

Table 33: Simulated Water Deficits for Two Set of Consecutives Dry Years by the Current Management-Penalty and the Drought Mitigation - Penalties Scenarios

Irrigation District	1936 Area-Weighted Deficit (mm)		
	Current Management - Penalties	**Drought Mitigation - Penalties**	**Difference with Current**
WID	174.8	174.6	-0.1
BRID	2.4	2.0	-0.3
EID	82.1	81.9	-0.2
LNID	192.8	192.8	0.0
Block 339	69.4	27.2	-42.1
Total	96.9	96.7	-0.2
Irrigation District	**1937 Area-Weighted Deficit (mm)**		
	Current Management - Penalties	**Drought Mitigation - Penalties**	**Difference with Current**
WID	95.6	95.6	0.0
BRID	45.6	31.3	-14.6
EID	93.4	92.3	-1.1
LNID	98.4	98.5	0.1
Block 339	404.5	275.9	-128.6
Total	81.0	76.5	-4.5
Irrigation District	**2000 Area-Weighted Deficit (mm)**		
	Current Management - Penalties	**Drought Mitigation - Penalties**	**Difference with Current**
WID	26.9	22.1	-4.8
BRID	0.0	0.0	0.0
EID	0.0	0.0	0.0
LNID	102.8	102.8	0.0
Block 339	0.0	0.0	0.0
Total	29.0	28.5	-0.5
Irrigation District	**2001 Area-Weighted Deficit (mm)**		
	Current Management - Penalties	**Drought Mitigation - Penalties**	**Difference with Current**
WID	153.3	153.3	0.0
BRID	1.7	1.4	-0.2
EID	87.2	85.8	-1.4
LNID	297.3	297.3	0.0
Block 339	133.6	114.2	-19.3
Total	122.8	122.2	-0.6

Figure 64 presents McGregor Reservoir levels for the years 1936 to 1938 for the two scenarios analysed as well as the Original WRMM. As shown graphically, operating McGregor Reservoir higher reduces the frequency at which McGregor is drawn down below the minimum level, permitting irrigators to divert directly from the reservoir.

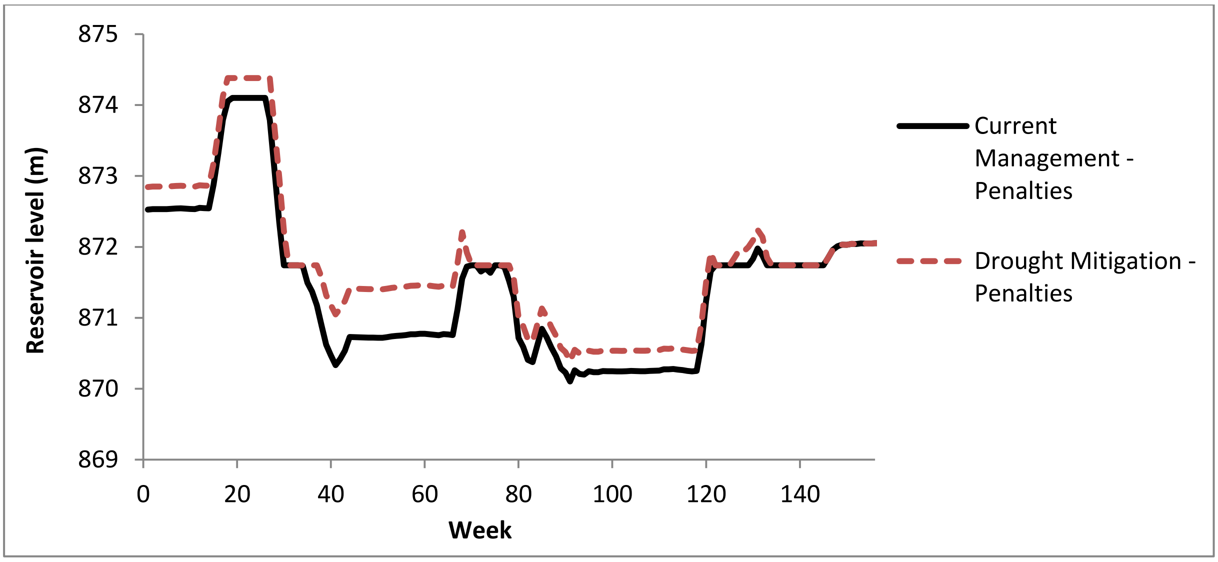


Figure 64: Simulated McGregor Level by Current Management – Penalties and the Drought Mitigation – Penalties Scenarios for the Years 1936-1938

Figure 65 presents the weekly water deficits of Block 339 for the same period (1936-1938) and shows that under the Drought Mitigation – Penalties scenario, Block 339's water deficits are reduced, even if the shortages occurring through the year 1937 are still severe.

Figure 66 and Figure 67 present McGregor and Travers-Little Bow levels for the years 2000 and 2001 as simulated by the two scenarios. Under the Drought Mitigation – Penalties scenario, both reservoir levels are higher in 2000. During the dry year of 2001, McGregor is still maintained higher when the ideal curves are increased, but the Travers-Little Bow level remained similar to the Current Management – Penalties simulated level, as this reservoir has a lower penalty for being drawn down. Under both scenarios the reservoir is drawn down to its lowest operating elevation, which might not be realistic. Indeed, the historical level of Travers reservoir is considerably higher than what is simulated by the model.

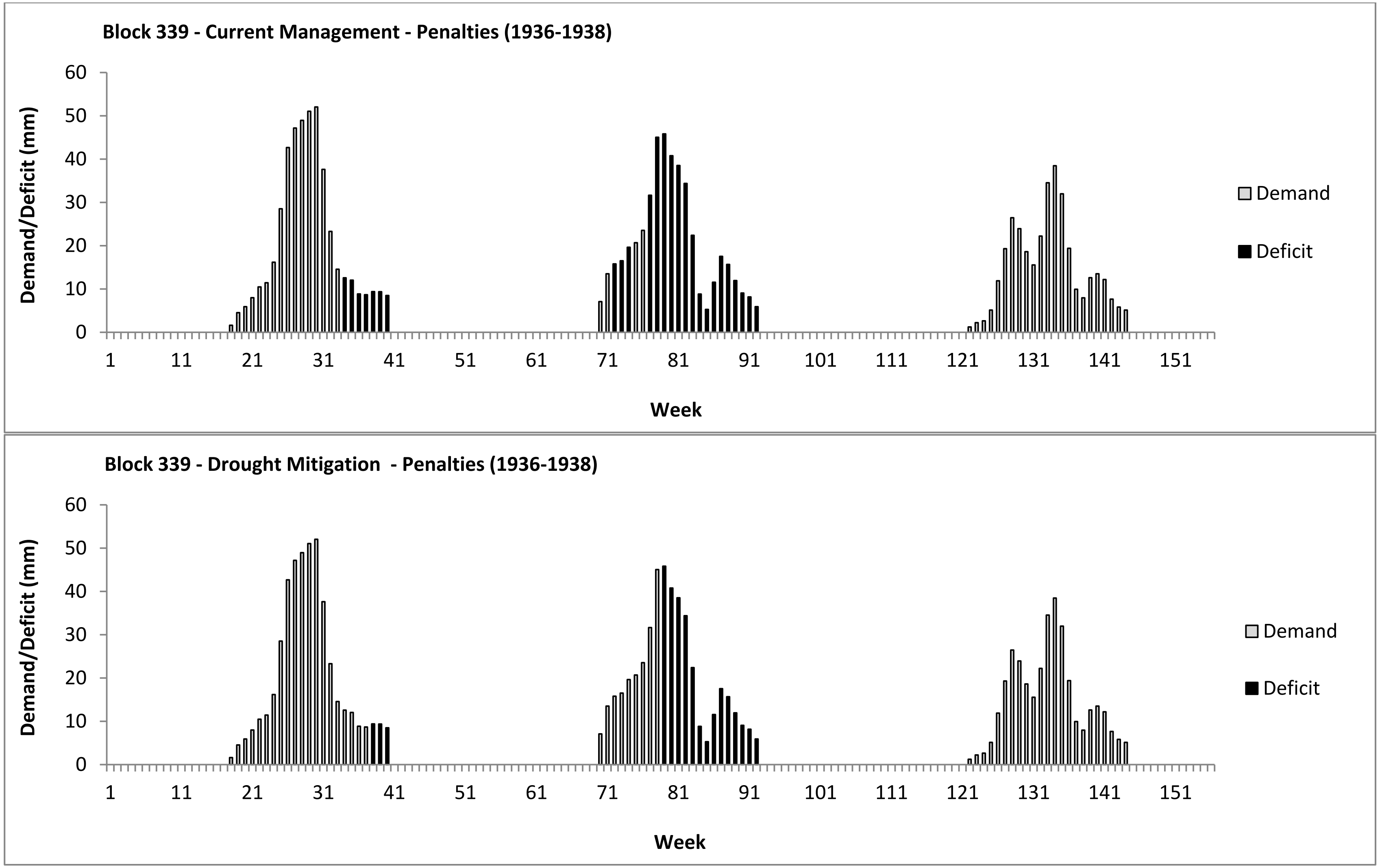


Figure 65: Simulated Weekly Deficits for Block 339 during the Years 1936-1938 by the Current Management – Penalties and Drought Mitigation – Penalties Scenarios

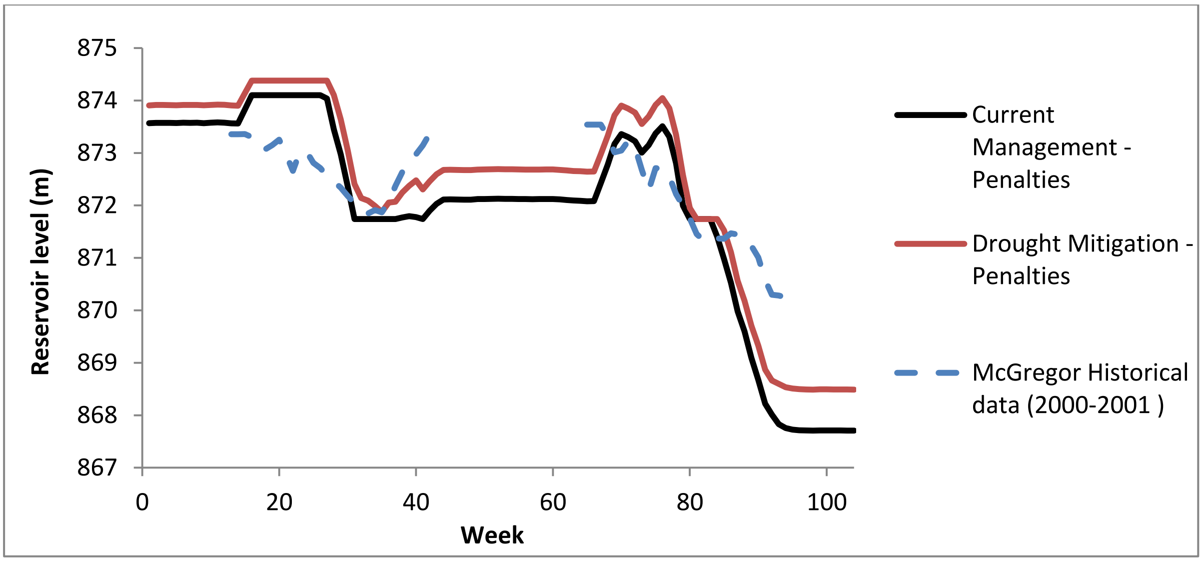


Figure 66: Simulated Weekly McGregor Levels during the Years 2000-2001 by the Current Management – Penalties and the Drought Mitigation – Penalties Scenarios

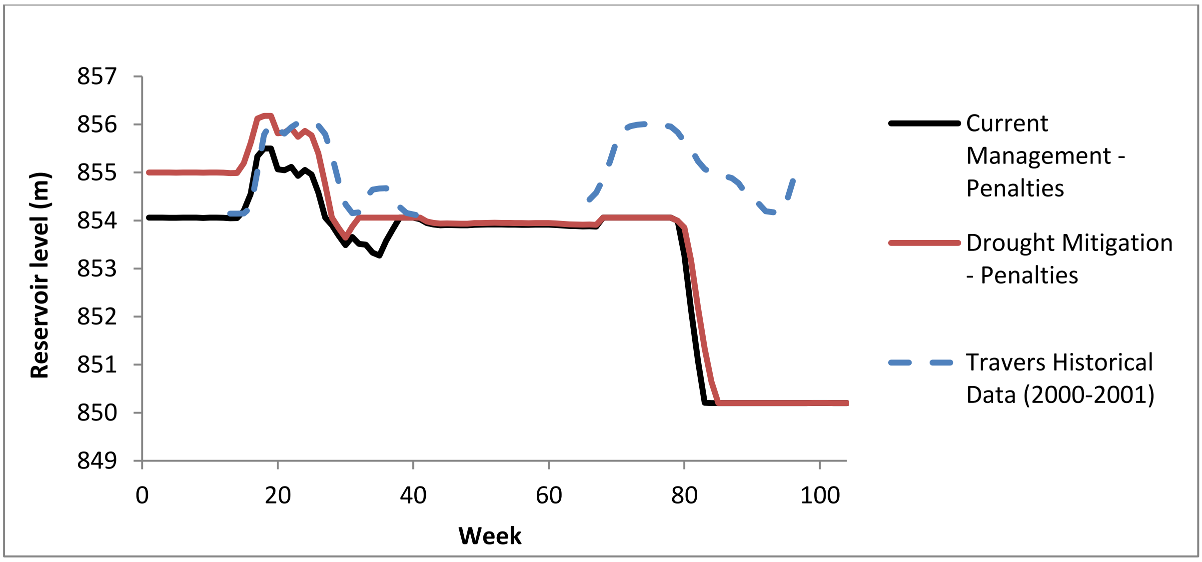


Figure 67: Simulated Weekly Travers-Little Bow Levels during the Years 2000-2001 by the Current Management – Penalties and the Drought Mitigation – Penalties Scenarios

5.2.4.4 Master Apportionment Agreement Performance

Regarding the Master Apportionment Agreement performance, changing the BRID's external reservoirs' ideal curves to mitigate drought impact decreases the flow passing the Saskatchewan border by about 930 dam^3 on average compared with the Current Management – Penalties scenario. However, during dry years the delivered flow is increased: in 1937 the flow is augmented to 50.11% instead of 50.03% and in 2001 the flow delivered becomes 47.73% instead of 47.52%. Therefore, more water is on average diverted by the BRID to fill the reservoirs maintained at a higher level, which diminishes the average flow delivery, but in dry years more water is passed downstream through return flows from the district.

5.2.4.5 BRID's Diversion Rates

Figure 68 shows the weekly diversion rate of the BRID for the scenarios analysed. Elevating the BRID's external reservoir ideal curves does not change the diversion rate compared to the Current Management – Penalties scenario for the month of July toward mid-August (week 28 to 33). However, the Drought Mitigation - Penalties scenario generates slightly higher diversion rates during the month of September (week 36 to 38). Moreover, as mentioned before, the diversion rate at the beginning of the season is reduced when the ideal curves of the BRID's reservoir are elevated, but this period of the year is less critical in terms of water quality. Therefore, the drought mitigation curves do not considerably improve or worsen the diversion rate performance compared with the Current Management – Penalties scenario.

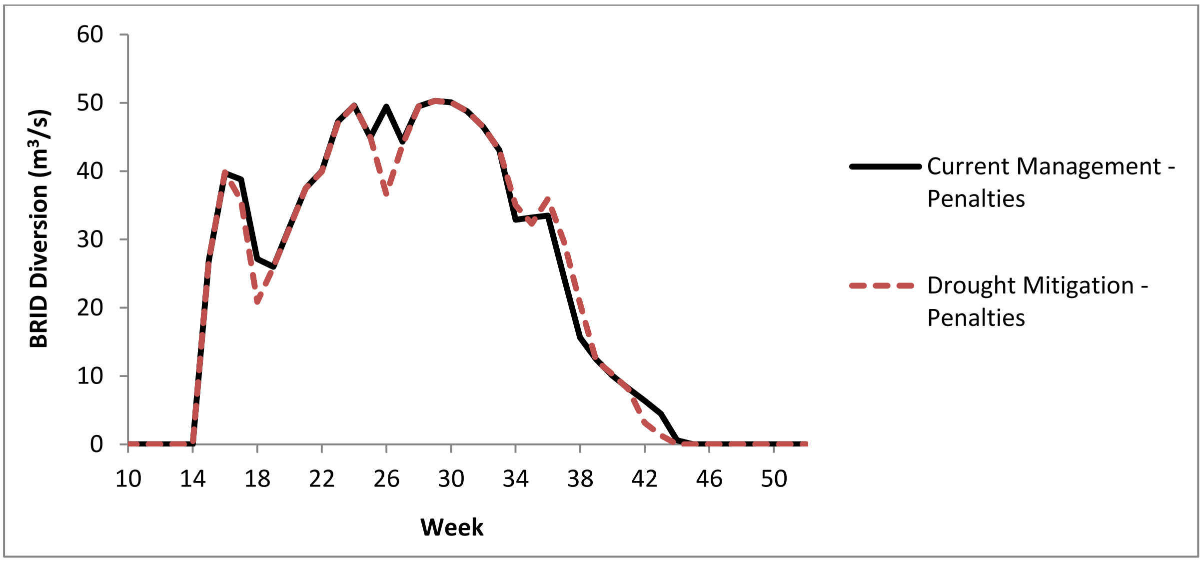


Figure 68: BRID's Average Weekly Diversion Rate in Carseland Canal for Three Typical Normal Years Simulated by the Current Management – Penalties and the Drought Mitigation Penalties Scenarios

5.2.4.6 BRID's Average Reservoir Levels

Figure 69 compares the average reservoir levels for the BRID obtained from current and drought mitigation ideal curves. As expected, McGregor and Travers Little Bow reservoirs are maintained higher on average under the Drought Mitigation – Penalties scenario. The average winter levels reached historically for McGregor become closer to the ones simulated, but the summer levels historically recorded are much lower than the ones modelled. It also is possible to notice that changing the ideal curves of the BRID's external reservoirs did not impact much the average level of the BRID's internal reservoirs.

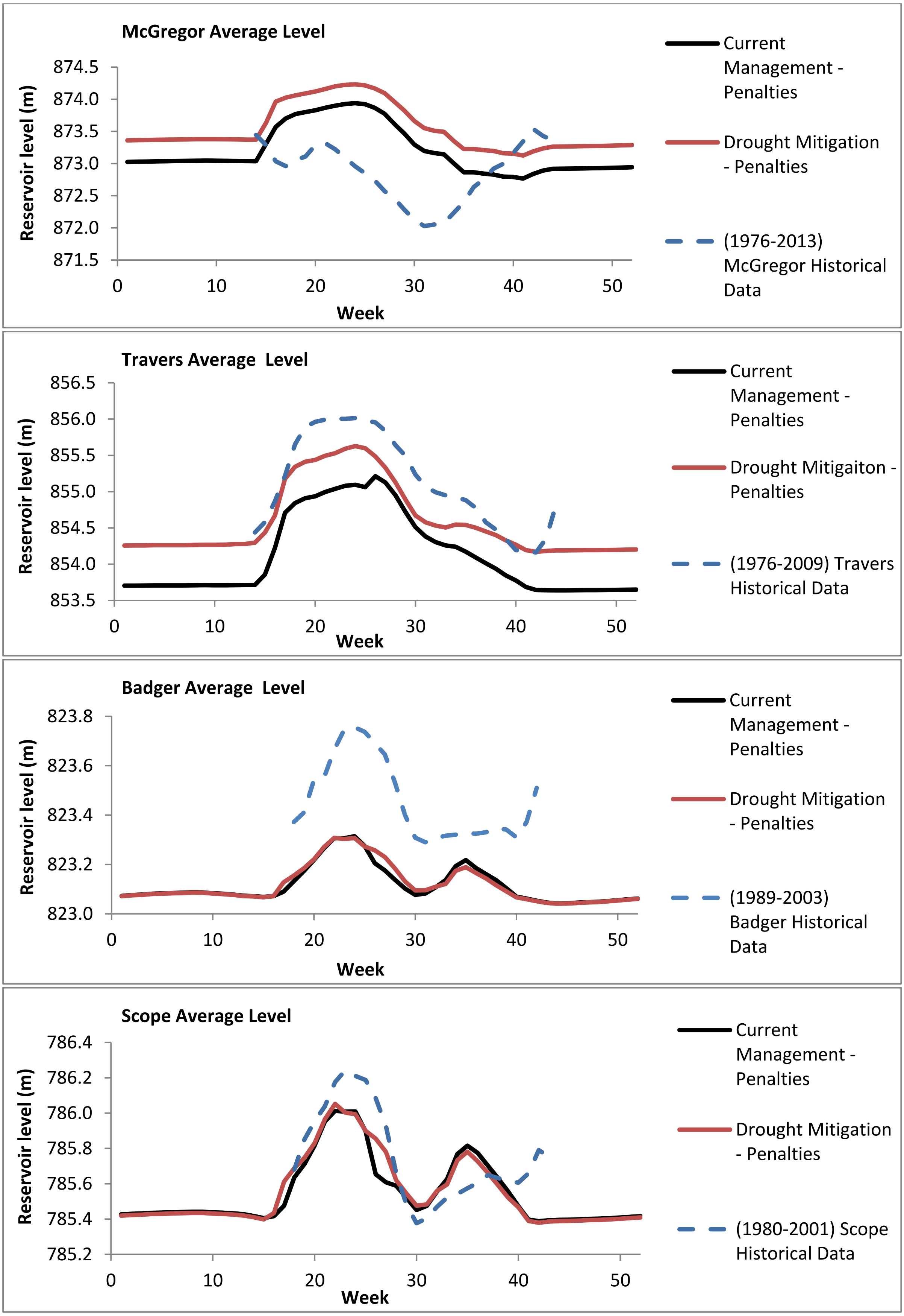


Figure 69: Simulated BRID's Reservoir Average Levels by the Current Management – Penalties and Drought Mitigation Penalties - Scenarios

5.2.4.7 Assessment of the Hypothesis

It was believed that elevating the ideal curves in the WRMM model for the BRID's external reservoirs to serve a drought mitigation purpose would increase the water supply available to meet irrigation demands. Based on the simulation results of the average water supply, the risk measures of the water deficits, and the Master Apportionment Agreement, the fifth hypothesis of the reservoir management analysis is validated. However, the difference between the Drought Mitigation – Penalty and the Current Management – Penalty version is relatively small. Indeed, the reliability and resiliency performances remained the same for both simulations, which would lead to the same results of risk assessment for irrigation development. Moreover, even if the water deficit performances were improved for all the districts when the BRID's reservoirs were operated under the drought mitigation ideal curves, the gains in water supply were observed mainly for the BRID and particularly for its more vulnerable irrigation block (Block 339). Therefore, changing the BRID's external reservoir rule curves to serve exclusively water supply purposes does not seem to provide sufficient benefits to considerably mitigate droughts impact compare to the current management practices modelled in the Current Management – Penalties scenario and it has the additional down side of possibly introducing additional flooding risks. Based on this analysis, it is believed that results simulated under the Original WRMM and the Current Management – Penalties scenarios should be assessed when evaluating irrigation risks for planning studies, but there is not enough potential benefits to analyse as well the results generated under the Drought Mitigation – Penalties scenario.

5.3 Results and Discussion for Future Scenarios of Irrigation Demand

The third objective of the research project aims to determine the available water supply in the Bow River Basin under different scenarios of irrigation demand for dry to wet hydrological conditions. To quantify the bounding water supply available for agriculture development, different combinations of IDM inputs with various reservoir management scenarios were compared.

Regarding the IDM inputs, the spectrum of irrigation demand scenarios were represented by three levels of water-use: the Reference Water-use scenario corresponds to the reference case, the Expansion – High Water-use scenario represents the highest irrigation demand conditions and the Low Water-use – Low Target scenario represents the lowest irrigation demands simulated. However, note that the full names of the Expansion – High Water-use and Low Water-use – Low Target scenarios are shortened to "High Water-use" and "Low Water-use" in this section to identify the main differences between them more clearly. Finally, an additional high water-use scenario identified as Bruce Lake Expansion – High Water-use scenario, which represents a larger expansion for the WID considering Bruce Lake is added to its water conveyance network is also investigated.

Three reservoir management scenarios were selected for further analysis under the low to high water-use conditions based on the previous analysis results: 1) the Original WRMM because it corresponds to the reservoir management reference version of the WRMM actually used by AEP, 2) the Current Management – Penalties scenario because it obtained the best overall performances among the scenarios representing the current BRID's operations, and 3) the Drought Mitigation – Penalties scenario as its provide the best performances in terms of meeting the irrigation demand even if it does not represent the current BRID's operations.

5.3.1 Water Supply Available under the Highest Water Demand Scenario

The first objective of the water supply analysis is to determine the risks for irrigation of the upper bound of irrigation demand for the Bow River Basin. Therefore, the two questions guiding the results analysis are:

1. How does the High Water-use scenario compare with the Reference Water-use case in terms of water supply available for irrigation?
2. Is the High Water-use scenario sustainable for the irrigation districts?

The quantification of the water supply available to meet the water demand is assessed by comparing the Original WRMM and the Current Management – Penalties model performances under both the Reference Water-use and the High Water-use input data. Indeed, it was believed that the risks for irrigation management should be assessed through both versions of the WRMM as it was found in the reservoir management analysis that the Current Management – Penalties version produced greater water supply results than the Original WRMM.

5.3.1.1 Simulated Water Supply for Dry to Wet Conditions

The average water supply simulated for dry to wet conditions by the two WRMM versions analysed is compared in Table 34 to Table 36. Table 34 presents the dry years results, which generated the highest disparities between the two reservoir management scenarios. Indeed, the highest water supply values are simulated using the Current Management – Penalties version of the WRMM. The area-weighted total water supply for the four irrigation districts generated under the High Water-use condition is increased from 407 to 429 mm by the updated WRMM version and from 402 to 403 mm under the Reference Water-use state.

More particularly, even if the BRID's volumetric water supply is higher under the High Water-use scenario compare with the reference case, the district's water supply per unit area decreases from 457 to 444 millimeters on average when the Original WRMM is used. It means that the model cannot meet the full additional demand of the BRID and on the contrary, the district suffers higher water deficits as its supply is divided over a greater area. However, when the Current Management – Penalties model is used, the BRID's higher demand per unit area could partly be met as its water supply increases from 465 millimeters simulated under the Reference Water-use to 511 millimeters under the High Water-use scenario. When the alternative WRMM model is used there is a difference of about 89,000 dam^3 of water that serves the greater irrigation demand compare to only about 22,000 dam^3 under the Original WRMM simulation.

In contrast, the LNID suffers a net decrease in water allocations under the Original WRMM and the Current Management – Penalties versions even if its water demand is increased by the High Water-use scenario. The water supplied to this district is further decreased by the Current Management – Penalties version compare with the Original WRMM when the Reference Water-use scenario is simulated but the inverse situation applies when the High Water-use scenario is simulated. The lower water supply allocated to this district is explained by the increased demand on the LNID's stored water to meet the Master Apportionment Agreement as the Bow River contributions are reduced when the irrigation demands are higher.

Both WRMM versions allocate more water to the WID and the EID under the High Water-use scenario with the greater increase experienced by the EID. Indeed, the WID is limited by its storage capacity, which restricts its delivered supply even if this district possesses the most senior licence.

Table 34: Water Supply for Three Average Dry Years (1936, 1949 and 2001) Simulated by the Original WRMM and Current Management-Penalty Scenarios under the Reference and High Water-use Conditions

Irrigation District	Reference Water-use		High Water-use		Difference Ref. to High Water-use	
	Original WRMM (mm)	Current Management – Penalties (mm)	Original WRMM (mm)	Current Management – Penalties (mm)	Original WRMM (dam^3)	Current Management – Penalties (dam^3)
WID	329.1	330.0	332.1	332.1	14,597	14,228
BRID	457.4	465.2	444.1	510.5	21,970	89,003
EID	457.8	455.6	486.7	488.6	54,184	59,219
LNID	293.5	291.9	284.5	289.0	-8,351	-2,679
Area-Weighted Total	402.2	403.4	407.2	428.9	82,400	159,771

Table 35 presents the normal year results, which generated only small disparities between the two reservoir management scenarios. In this case, the four districts' area-weighted water supply available in normal years for the Reference Water-use scenario is approximately 347 mm compared to 378 mm under the High Water-use scenario as simulated by both WRMM versions. The water supply per unit area difference is equivalent to a volume of about 171,000 to 172,000 dam^3 according to the WRMM version used.

Table 35: Water Supply for Three Average Normal Years (1959, 1962 and 1964) Simulated by the Original WRMM and Current Management-Penalty Scenarios under the Reference and High Water-use Conditions

Irrigation District	Reference Water-use		High Water-use		Difference Ref. to High Water-use	
	Original WRMM (mm)	Current Management – Penalties (mm)	Original WRMM (mm)	Current Management – Penalties (mm)	Original WRMM (dam^3)	Current Management – Penalties (dam^3)
WID	307.6	306.9	342.6	343.7	27,297	28,048
BRID	345.9	345.9	395.5	395.5	84,115	84,115
EID	381.1	381.1	405.2	405.2	45,180	45,180
LNID	318.1	318.1	334.3	334.3	14,887	14,873
Area-Weighted Total	347.0	346.9	378.0	378.1	171,479	172,216

Table 36 presents the wet year results, which generated almost the same water supply values under the two reservoir management scenarios. Indeed, during surplus years the districts' diversions are not limited and, as a result, both models can supply close to the full districts' water demands. The change in irrigation demands generated an increased in water supply of approximately 30 mm over the normal and dry conditions. The four districts water supply available in wet years for the Reference Water-use scenario is approximately 269 mm and is about 303 mm for the High Water-use scenario. This increase corresponds to a volume of about 171,000 dam^3 for the four districts combined, which is a similar volume than the one estimated for the normal years.

Table 36: Water Supply for Three Average Wet Years (1954, 1965 and 1981) Simulated by the Original WRMM and Current Management-Penalty Scenarios under the Reference and High Water-use Conditions

Irrigation District	Reference Water-use		High Water-use		Difference Ref. to High Water-use	
	Original WRMM (mm)	Current Management – Penalties (mm)	Original WRMM (mm)	Current Management – Penalties (mm)	Original WRMM (dam^3)	Current Management – Penalties (dam^3)
WID	209.8	209.8	240.0	240.0	21,352	21,342
BRID	280.8	280.8	324.2	324.2	71,915	71,915
EID	296.5	296.5	327.7	327.7	51,190	51,190
LNID	241.6	241.6	270.2	270.2	26,306	26,306
Area-Weighted Total	268.7	268.7	302.8	302.8	170,763	170,753

5.3.1.2 Risk Measures for Water Deficits

The risk measures of the water deficits simulated under the Reference Water-use scenario by the Original WRMM and the Current Management – Penalties models are presented in Table 37. The performance of both WRMM versions is similar. All the districts suffer acceptable risks for irrigation over the study period of 74 years. Indeed, the LNID's reliability of 0.93 is the lowest of the four districts but it is still above the threshold value of 0.90. Moreover, the LNID has a perfect resilience of 1, which means it never experiences back to back severe water deficits. In fact, the only district experiencing two consecutive severe deficits is the EID. The performance of Block 339 is also indicated as its water shortages could be increased under the Current Management – Penalties simulation. However, both WRMM versions show acceptable risks performances for this block under the Reference Water-use scenario.

Table 37 : Risk Measures of the Water Deficits (1928-2001) for the Original WRMM and Current Management-Penalty Scenarios under the Reference Water-use Condition

Irrigation District	Reliability		Resilience		Vulnerability	
	Original WRMM	Current Management – Penalties	Original WRMM	Current Management – Penalties	Original WRMM	Current Management – Penalties
WID	0.95	0.95	1.00	1.00	36.93	36.13
BRID	1.00	1.00	1.00	1.00	0.00	1.41
EID	0.98	0.97	0.85	0.88	20.64	19.82
LNID	0.93	0.93	1.00	1.00	57.40	58.35
Block 339	1.00	0.99	1.00	1.00	0.00	112.94
Area-Weighted Total	0.97	0.97	0.95	0.96	25.71	25.99

The risk measures of the water deficits simulated under the High Water-use scenario for the two WRMM versions are presented in Table 38. In this case, the performances of both WRMM models vary slightly. The Current Management – Penalties improves the performance of the BRID while it decreases that of Block 339. This WRMM version also improves slightly the reliability of the WID, the resiliency of the EID and the vulnerability of the LNID, but increases the vulnerability of the WID and the EID. Even if some variations exist between the risk measures of both WRMM models, they still provide similar results in terms of irrigation development sustainability. Indeed, under the water stressed conditions generated by the High Water-use scenario, the districts suffer severe water deficits more often compared to the Reference Water-use scenario. More particularly, the LNID and the WID's reliability is below the threshold value of 0.90, which means that these districts experience water shortages greater than 100 millimeters in more than 10% of the years simulated. Moreover, the LNID' resilience value is only 0.66, which indicates that back-to-back severe water deficits occur one-third of the time. Therefore, it is concluded that irrigation management under the High Water-use conditions presents unacceptable risks for the WID and the LNID.

Table 38 : Risk Measures of the Water Deficits (1928-2001) for the Original WRMM and Current Management-Penalty Scenarios under the High Water-use Condition

	Reliability		**Resilience**		**Vulnerability**	
Irrigation District	**Original WRMM**	**Current Management – Penalties**	**Original WRMM**	**Current Management – Penalties**	**Original WRMM**	**Current Management – Penalties**
WID	0.86	0.87	0.90	0.90	39.10	40.84
BRID	0.98	0.99	0.95	0.93	39.55	15.23
EID	0.97	0.97	0.85	0.89	23.36	24.18
LNID	0.87	0.87	0.66	0.66	78.64	77.29
Block 339	1.00	0.92	1.00	0.67	0.00	115.85
Area-Weighted Total	0.94	0.94	0.84	0.85	43.46	36.30

Figure 70 to Figure 73 present graphically the recurrence and severity of the area-weighted deficits per district over the study period for the Reference and High Water-use scenarios. As both WRMM models produced similar results, only the Original WRMM outputs are reported. It could be observed that the majority of the severe water deficits occur during the Dust Bowl Period; the successive dry years that took place in the Thirty's. Moreover, the WID and the LNID suffer water deficits, which are several times the magnitude of the water deficits experienced by the EID and the BRID.

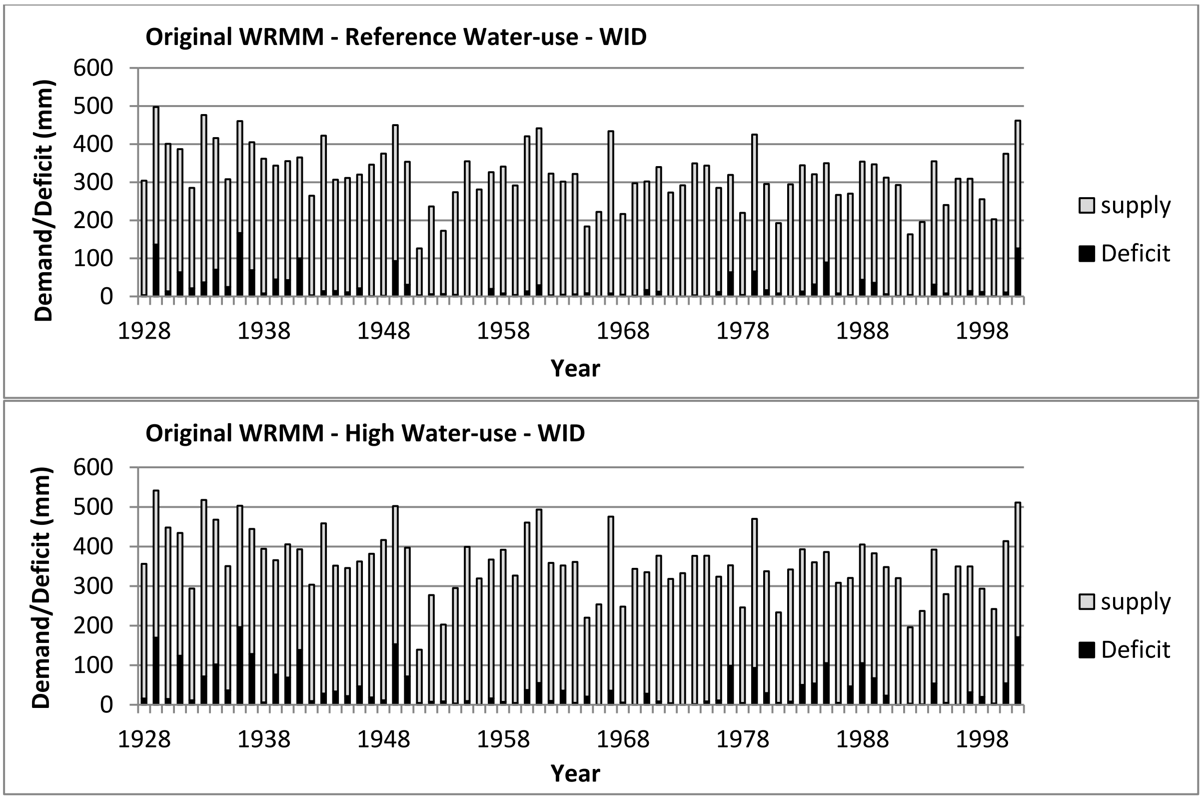


Figure 70: Simulated Area-Weighted Deficits for the WID by the Original WRMM Scenario over the Study Period (1928-2001) and under the Reference and High Water-use Conditions

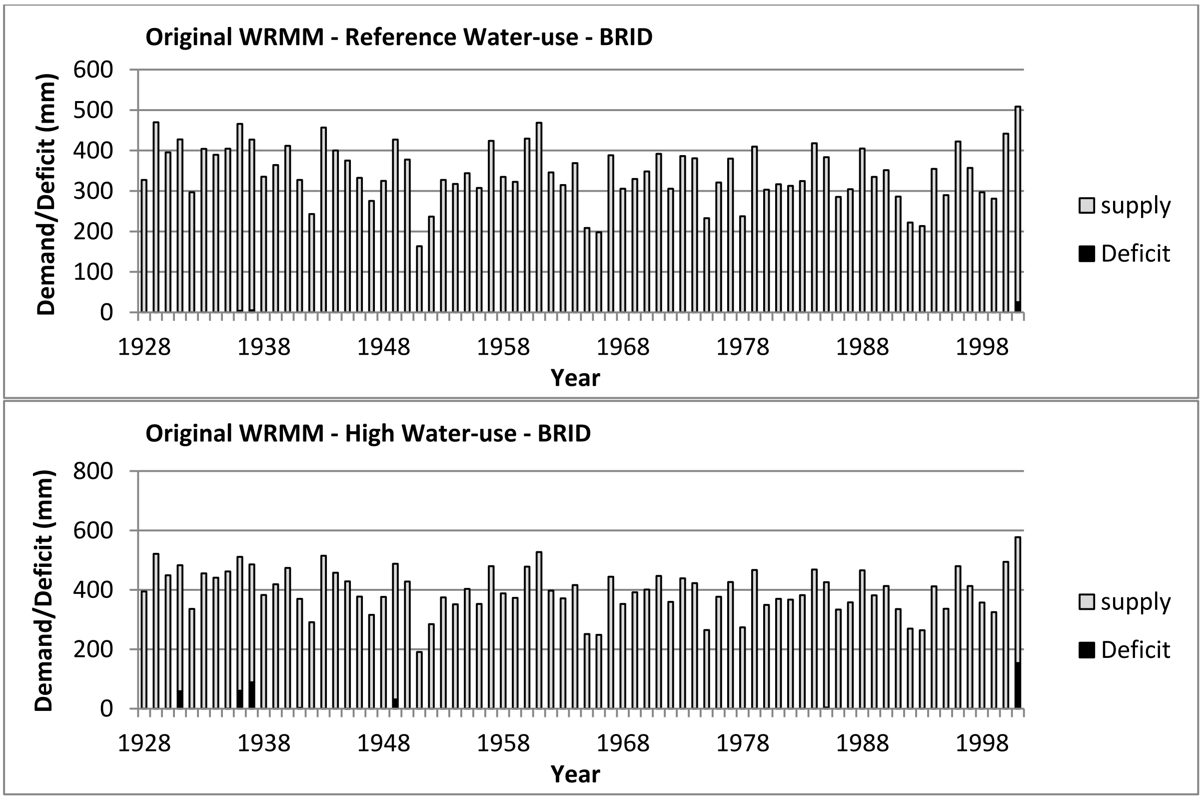


Figure 71: Simulated Area-Weighted Deficits for the BRID by the Original WRMM Scenario over the Study Period (1928-2001) and under the Reference and High Water-use Conditions

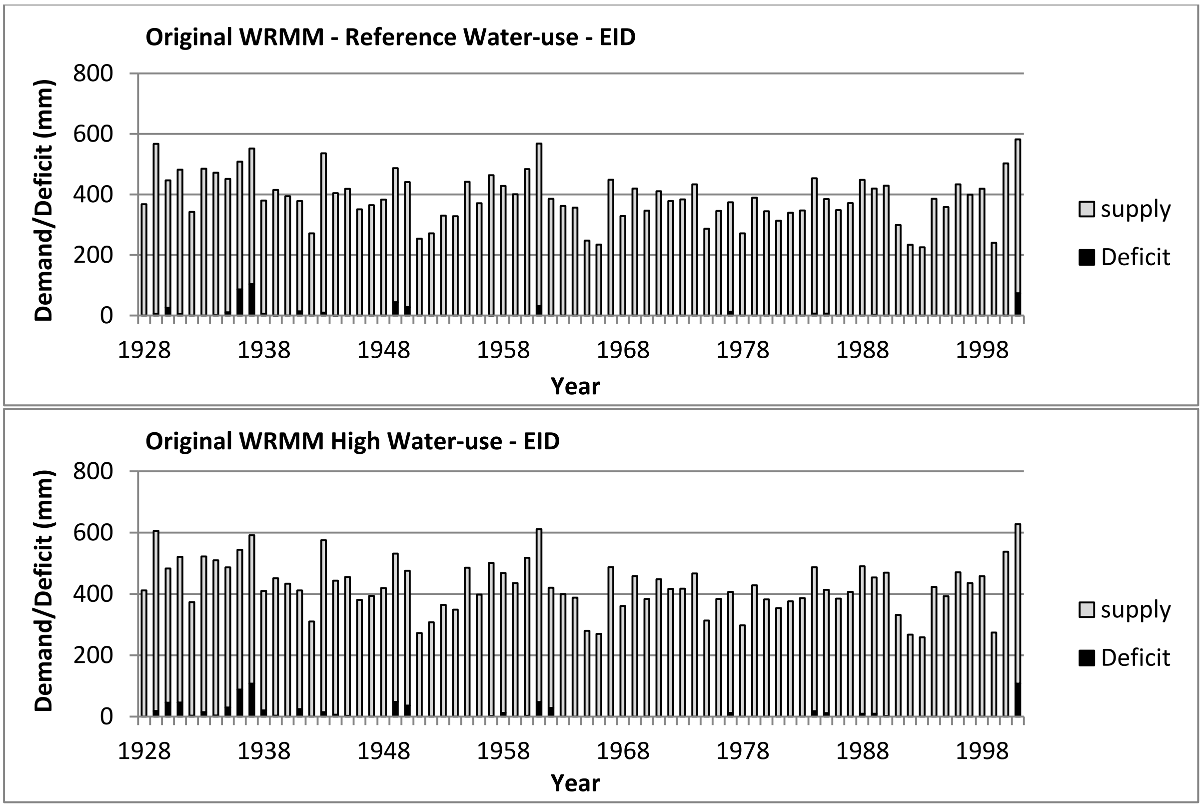


Figure 72: Simulated Area-Weighted Deficits for the EID by the Original WRMM Scenario over the Study Period (1928-2001) and under the Reference and High Water-use Conditions

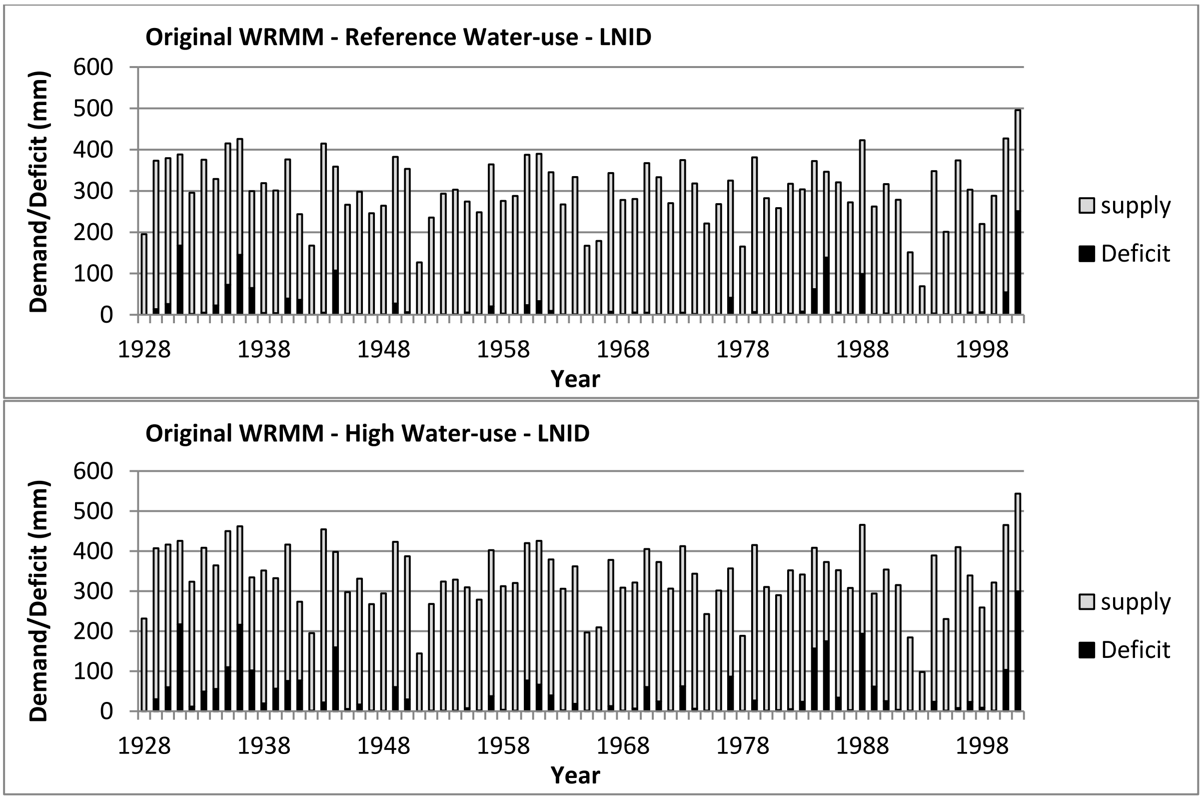


Figure 73: Simulated Area-Weighted Deficits for the LNID by the Original WRMM Scenario over the Study Period (1928-2001) and under the Reference and High Water-use Conditions

5.3.1.3 Typical Dry-year Water Deficits

The differences in the magnitudes of water deficits occurring in typical dry years for the two scenarios of irrigation demand simulated by each WRMM model are presented in Table 39 and Table 40. Note that the High Water-use scenario increases the area-weighted deficit of the four districts above the threshold value of 100 mm for 1936's drought under both WRMM simulations. Furthermore, the shortage in water occurring during the dry year of 1949 remains acceptable under the two water-use scenarios.

As was the case for the water supply, the two WRMM versions produce closer results under the Reference Water-use scenario compared with the High Water-use scenario. Indeed, under the High Water-use case, the dry-year shortages simulated by the Current Management – Penalties model are decreased globally for the four districts compared to the results simulated by the Original WRMM.

Table 39: Simulated Water Deficits for Three Typical Dry Years by the Original WRMM under the Reference and High Water-use Condition

	1936 Area-Weighted Deficit (mm)			1949 Area-Weighted Deficit (mm)			2001 Area-Weighted Deficit (mm)		
Irrigation District	Reference Water-use	High Water-use	Diff. with Reference	Reference Water-use	High Water-use	Diff. with Reference	Reference Water-use	High Water-use	Diff. with Reference
WID	166.4	196.3	29.9	93.1	153.0	59.9	126.0	170.7	44.7
BRID	3.7	60.5	56.8	0.2	31.0	30.8	25.3	153.4	128.1
EID	86.3	88.3	2	44.2	47.8	3.6	73.9	107.2	33.3
LNID	145.3	216.1	70.8	27.2	60.1	32.9	251.0	299.6	48.6
Block 339	0.0	0.0	0	17.3	21.5	4.2	10.9	10.6	-0.3
Total	85.8	123.2	37.4	32.3	57.6	25.3	110.3	175.1	64.8

Table 40: Simulated Water Deficits for Three Typical Dry Years by the Current Management – Penalties model under the Reference and High Water-use Conditions

	1936 Area-Weighted Deficit (mm)			1949 Area-Weighted Deficit (mm)			2001 Area-Weighted Deficit (mm)		
Irrigation District	Reference Water-use	High Water-use	Diff. with Reference	Reference Water-use	High Water-use	Diff. with Reference	Reference Water-use	High Water-use	Diff. with Reference
WID	165.3	196.16	30.9	93.1	153.0	59.9	124.2	170.7	46.5
BRID	5.2	22.9	17.7	0.2	0.5	0.3	0.5	22.4	21.9
EID	90.2	86.6	-3.6	45.3	46.8	1.5	75.1	104.5	29.4
LNID	150.2	204.7	54.5	27.2	60.1	32.9	251.0	297.3	46.3
Block 339	17.5	145.5	128.0	17.3	40.2	22.9	40.6	194.3	153.7
Total	88.7	108.6	19.9	32.7	48.1	15.4	103.3	134.2	30.9

5.3.1.4 Master Apportionment Agreement Performance

Regarding the Master Apportionment Agreement performance, changing the water demand input data from the Reference Water-use to the High Water-use decreases on average the flow passing the Saskatchewan border by about 150,500 dam^3 under the Original WRMM version and by about 152,700 dam^3 under the Current Management – Penalties version. As a consequence, the number of years for which the delivery are below 50% increases from two years (1931 and 2001) to four years in the case of the Original WRMM (1931, 1937, 1939 and 2001) and three years in the case of the Current Management – Penalties model (1931, 1937 and 2001). Moreover, in the case of the High Water-use scenario, the 2001 flow falls below the threshold value of 48% for both WRMM models; 46.82% for the Original WRMM and 47.18 % for the Current Management – Penalties version.

5.3.1.5 BRID's Diversion Rates

The weekly diversion rates of the BRID for the scenarios analysed are presented in Figure 74. As shown, increasing the water-use logically results in higher diversion rates, particularly for the month of September (weeks 35 to 38), which is less critical in terms of water temperature. During the months of July and August (weeks 27 to 34), the diversion rates are slightly increased for the Original WRMM when the High Water-use scenario is simulated and remain the same when the Current Management – Penalties model is used. However, the Current Management – Penalties model generates higher diversion rates for these months than the Original WRMM, which could impact more the water quality downstream of the BRID.

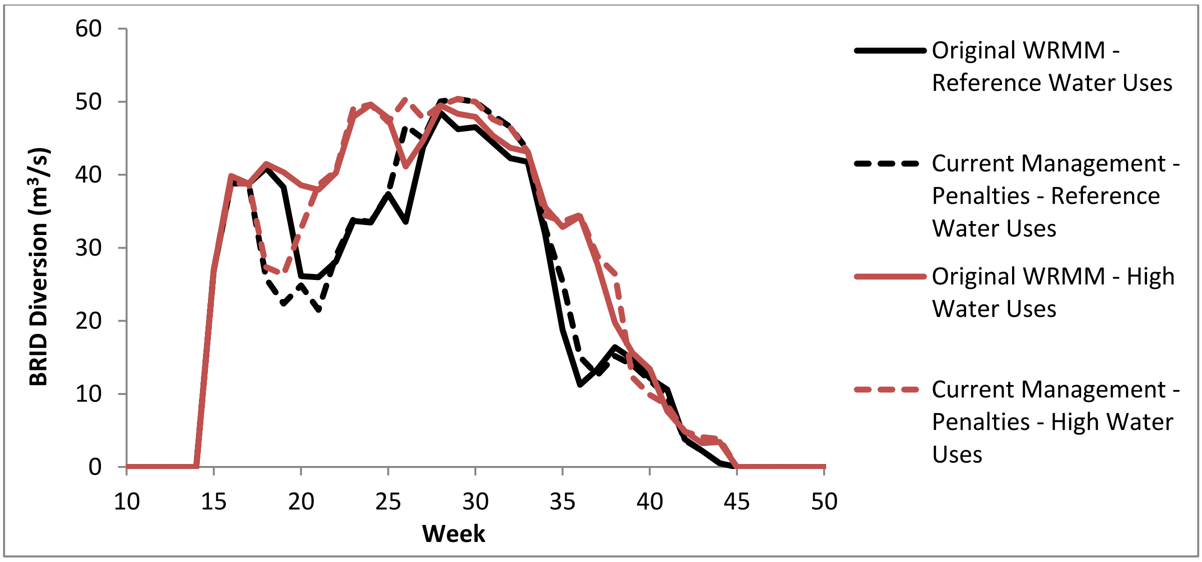


Figure 74: BRID's Average Weekly Diversion Rate in Carseland Canal for Three Typical Normal Years Simulated by the Original WRMM and the Current Management – Penalties Scenarios under the Reference and High Water-use Conditions

5.3.1.6 Lessons Learned

The first objective of the water supply analysis aims to determine the risks for irrigation of the highest water-demand scenario. It was determined that the High Water-use scenario generated a required water supply per unit area of about 30 millimeters greater than the Reference Water-use case. Indeed, the area-weighted water supply available for the four districts varies for dry to wet conditions from 270 to 400 millimeters in the case of the reference Water-use scenario and from 300 to 430 mm in the case of the High Water-use scenario using the Current Management – Penalties model. The highest water supply reached in dry years under the High Water-use scenario is reduced to about 410 millimeters under the Original WRMM simulation.

Even, if the Current Management – Penalties scenario permitted allocation of a greater volume of water on average, the risk measures of the water deficits generated by both WRMM versions were similar. While there is no water deficit risk associated with the Reference Water-use scenario for any of the four irrigation districts simulated in the Main SSRB model of the WRMM, further expansion of the land irrigated combined with a crop mix of higher water requirement simulated under the High Water-use scenario is unsustainable for the LNID and the WID, the two districts with the lowest reliability. Furthermore, under the High Water-use scenario, both WRMM models could not deliver the minimum flow at the Saskatchewan border to meet the Master Apportionment Agreement as the adjusted minimum percentage of 48% was not reached in at least one year of the simulation period.

The High Water-use scenario represented extremely high water demands that are unlikely to occur at the entire Bow River Basin scale. It was nonetheless useful to determine that the BRID and the EID could still reach this level of irrigation intensity with acceptable risks. Finally, it has to be emphasized that the preceding analysis was made using historical climatic and hydrologic data sets, whereas climate change studies are demonstrating the non-stationary of the hydrological and climatic conditions (Milly *et al.* 2005; Rood *et al.* 2008). Therefore, the irrigation sector sustainability could be threatened by more severe and unprecedented droughts, which were not captured in the available historical data.

5.3.2 Water Supply Available under Drought Mitigation Management for the Highest Water Demand Scenario

The second objective of the water supply analysis intended to determine if the Drought Mitigation – Penalties version of the WRMM could lower the risks for irrigation of the High Water-use scenario representing water stressed conditions. In the reservoir management analysis section, it was determined that this particular version of the WRMM did not provide enough benefits over the Current Management – Penalties model to justify further analysis. It is nonetheless useful to determine if the Drought Mitigation – Penalties scenario could mitigate the risks for irrigation for the upper bounding scenario of irrigation level. The third question guiding the results analysis is:

3. Could managing the BRID's external reservoir solely for drought mitigation reduce the risks for irrigation under the High Water-use scenario?

To assess the third question, the Current Management – Penalties model performance is compared with the Drought Mitigation – Penalty model performance. As the two approaches produced similar results, only the key lessons learned from the comparison of the two models' results are further presented.

5.3.2.1 Lessons Learned

It was determined that the additional water supply provided by the Drought Mitigation – Penalties model was not sufficient to lower the risks of the two most vulnerable districts, the WID and the LNID. Furthermore, this WRMM version produced a higher diversion rate in late summer and its average flow deliveries at the Saskatchewan border was comparable to those simulated by the Current Management – Penalties version.

5.3.3 Bruce Lake Reservoir Impact on the Water Supply Available for the Highest Water Demand Scenario

The third objective of the reservoir management analysis was to assess the water supply gains that could be obtained from the construction of Bruce Lake reservoir in the WID. This would permit definition of the upper limit of water supply available under the worst case scenario in terms of water-use, but the best scenario in terms of the WID's storage capacity. The fourth and fifth questions guiding the results analysis are as follow:

4. Could the addition of Bruce Lake reservoir considerably lower the risks for irrigation of the WID to an acceptable level for the extreme water stressed conditions represented by the High Water-use scenario?
5. Is an additional expansion of the WID's irrigated area possible as represented by the Bruce Lake Expansion – High Water-use scenario considering the additional water supply provided by Bruce Lake reservoir?

The fourth question of the water supply analysis is answered by comparing the performances of the Current Management – Penalties scenario with the Bruce Lake – Current Management scenario for the High Water-use input data, because the only difference between the two WRMM versions is the addition of Bruce Lake reservoir in the WID's network. The Current Management – Penalties version of the WRMM was used as the reference model instead of the Original WRMM because it represents more closely the BRID's current operations and provided the most optimal water supply results. Therefore, it should provide a better level of comparison to assess the net benefits of adding Bruce Lake reservoir in the WID network.

To assess the fifth question of the water supply analysis the performances of Bruce Lake – Current Management model was evaluated for the IDM input representing an additional expansion limit for the WID.

5.3.3.1 Simulated Water Supply for Dry to Wet Conditions

Table 41 presents the average water supply available for three typical dry years as simulated by the Current Management – Penalties models with and without Bruce Lake reservoir under the High Water-use and the Bruce lake Expansion – High Water-use scenarios. Logically, the water supply allocated to the WID is increased considerably through the additional stored water in Bruce Lake. Indeed, the water allocations are increased by about 23,000 dam^3 on average under the High Water-use scenario, which corresponds to 10.7% of the WID's average demand over the three typical dry years. In other words, about 10.7% of the WID's high water-use demand can only be met with the help of Bruce Lake reservoir during dry conditions. On the other hand, the additional water diverted to meet the WID's water requirement is taken away from the BRID and the LNID districts, reducing their respective water supply under the Bruce Lake – Current Management simulation. Indeed, the LNID's storage has to serve a greater portion of the Master Apportionment Agreement while the BRID's diversions are reduced as a consequence of its lower licence seniority compared to the WID. The EID's water supply is also increased slightly when Bruce Lake reservoir is simulated. Overall, the total area-weighted supply for the four districts reaches 433 millimeters per unit area instead of 429 mm due to the additional water provided by Bruce Lake.

When the WID's irrigated area is further expanded through the Bruce Lake Expansion – High Water-use scenario, about the same additional amount of water could be supplied to the WID with Bruce Lake reservoir (23,000 dam^3); however, the district's irrigation depth per unit area is reduced as a result of the additional land irrigated. Indeed, the water supply decreases from 386 millimeters to about 337 millimeters when the WID's expansion limit is further increased. Therefore, the additional water storage provided by Bruce Lake is not sufficient to compensate the increase in irrigation demand resulting from the WID's greater expansion.

Furthermore, the water supply of the BRID and the LNID is still reduced when the Bruce Lake Expansion – High water-use scenario is used. In fact, the total water supply for the four districts is reduced to 425 millimeters per unit area instead of 433 mm. In terms of water volume, Bruce Lake reservoir provides an increased volume of about 16,000 dam^3 compared with the Current Management – Penalty model under the High Water-use scenario and only an increase of about 12,000 dam^3 under the Bruce Lake Expansion – High Water-use scenario.

In summary, the highest water supply values during dry years are simulated using the Bruce Lake – Current Management model combined with the High Water-use scenario representing a more sustainable expansion of the WID.

Table 41: Water Supply for Three Average Dry Years (1936, 1949 and 2001) Simulated by the Original WRMM and Current Management-Penalty Scenarios under the Reference and High Water-use Conditions

	High Water-use			**Bruce Lake Expansion - High Water-use**	
Irrigation District	**Current Management – Penalties (mm)**	**Bruce Lake – Current Management – Penalties (mm)**	**Difference with Current (dam^3)**	**Bruce Lake – Current Management – Penalties (mm)**	**Difference with Current (dam^3)**
WID	332.1	386.2	22,997	337.3	22,693
BRID	510.5	509.9	-611	509.5	-1,070
EID	488.6	489.1	678	488.9	507
LNID	289.0	281.1	-7,213	277.9	-10,175
Area-Weighted Total	428.9	433.1	15,851	425.2	11,955

Table 42 presents the normal years results, which generated smaller disparities between the two reservoir management versions of the WRMM. Indeed, the water supplied to the WID is increased by the stored water in Bruce Lake by only 3 millimeters per unit area when the High Water-use scenario is simulated. On the other hand, simulating a higher expansion of the WID under the Bruce Lake Expansion – High Water-use scenario increases the overall water supply allocated to the WID by about 13,000 dam^3 compared to the WRMM version lacking the Bruce Lake Reservoir. As the extra water is distributed over a greater area, the irrigation depth is reduced on average to 327 millimeters as opposed to 344 millimeters. Similarly to what was observed previously, in the case of the normal year conditions, the highest volume of water supply is simulated using the Bruce Lake – Current Management model combined with the Bruce Lake Expansion – High Water-use scenario but the highest water supply per unit area values are under the High Water-use scenario representing a more sustainable expansion of the WID.

Table 42: Water Supply for Three Average Normal Years (1959, 1962 and 1964) Simulated by the Original WRMM and Current Management-Penalty Scenarios under the Reference and High Water-use Conditions

	High Water-use			**Expansion - High Water-use**	
Irrigation District	**Current Management – Penalties (mm)**	**Bruce Lake – Current Management – Penalties (mm)**	**Difference with Current (dam^3)**	**Bruce Lake – Current Management – Penalties (mm)**	**Difference with Current (dam^3)**
WID	343.7	346.9	1,391	327.0	12,775
BRID	395.5	395.5	0	395.5	0
EID	405.2	405.2	0	405.3	68
LNID	334.3	334.3	4	334.3	-3
Area-Weighted Total	378.1	378.5	1,394	375.5	12,839

Table 43 presents water supply values simulated under the wet years, which generated similar results to what was identified for the normal years. Indeed, during surplus years the WID's diversions are increased when Bruce Lake is added to its network, but the allocated water per unit area is reduced when a greater expansion of the WID's irrigated area is simulated. The highest water supply values per unit area are therefore obtained again with the Bruce Lake – Current Management model under the High Water-use scenario, which is about 304 millimeters and the highest volume of water supply values are simulated using the Bruce Lake – Current Management model combined with the Bruce Lake Expansion – High Water-use scenario.

Table 43: Water Supply for Three Average Wet Years (1954, 1965 and 1981) Simulated by the Original WRMM and Current Management-Penalty Scenarios under the Reference and High Water-use Conditions

	High Water-use			**Expansion - High Water-use**	
Irrigation District	**Current Management – Penalties (mm)**	**Bruce Lake – Current Management – Penalties (mm)**	**Difference with Current (dam^3)**	**Bruce Lake – Current Management – Penalties (mm)**	**Difference with Current (dam^3)**
WID	240.0	247.2	3,041	230.0	9,672
BRID	324.2	324.2	0	324.2	0
EID	327.7	327.7	0	327.7	0
LNID	270.2	270.2	0	270.2	0
Area-Weighted Total	302.8	303.6	3,041	300.5	9,672

5.3.3.2 Risk Measures of the Water Deficits

The risk measures of the water deficits simulated under the High Water-use scenario for the Current Management – Penalties and the Bruce Lake – Current Management models are presented in Table 44. The reliability of the WID is increased substantially by Bruce Lake reservoir as it changes from a too risky value of 0.87 to a reliability of 0.94, which is considered acceptable for irrigation management. Moreover, the resilience and vulnerability of the WID are also improved under the Bruce Lake – Current Management scenario. For the remaining districts, the performances obtained under both WRMM versions are comparable in terms of water security. Indeed, the LNID reliability is still below the threshold value of 0.90 and its resilience remains low while the BRID and the EID districts still experience acceptable water deficits.

Table 44 : Risk Measures of the Water Deficits (1928-2001) Simulated by the Current Management-Penalty and Bruce Lake – Current Management Models under the High Water-use Condition

	Reliability		**Resilience**		**Vulnerability**	
Irrigation District	**Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**	**Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**	**Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**
WID	0.87	0.94	0.90	0.91	40.84	35.62
BRID	0.99	0.99	0.93	0.95	15.23	13.12
EID	0.97	0.97	0.89	0.85	24.18	22.27
LNID	0.87	0.87	0.66	0.67	77.29	79.09
Area-Weighted Total	0.94	0.95	0.85	0.84	36.30	34.86

Table 45 presents the risk measures of the water deficits simulated under the Bruce Lake Expansion – High Water-use scenario by the Bruce Lake – Current Management model. Logically, because this scenario represents a greater increase of irrigated land, the risk measures of water deficits for the WID are worsened compare to those obtained under the High Water-use conditions. However, the WID reliability's is still acceptable as severe water deficits occur in less than 10% of the years simulated. Moreover, the performances of the other districts are almost not affected. Therefore, it is considered that Bruce Lake reservoir provides to the WID more water security, which could permit to this district to reach a greater level of expansion even if a high water-use crop mix is grown. However, excessive expansion could lead to the same water shortages than the ones experienced without Bruce Lake reservoir as WID's reliability is only slightly above the threshold reliability of 0.90.

Table 45 : Risk Measures of the Water Deficits (1928-2001) for the Current Management-Penalty and Drought Mitigation – Penalties Scenarios under the Bruce Lake Expansion - High Water-use Condition

	Reliability	Resilience	Vulnerability
Irrigation District	**Bruce Lake – Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**
WID	0.91	0.84	45.91
BRID	0.99	0.95	13.05
EID	0.97	0.89	23.96
LNID	0.87	0.66	79.57
Area-Weighted Total	0.94	0.85	36.84

5.3.3.3 Typical Dry Year Water Deficits

The difference in the magnitude of the water deficits occurring in typical dry years was also compared for both WRMM models under the two water-use scenarios as presented in Table 46. It could be noted that the addition of Bruce Lake reservoir in the WID's network reduces its water deficits considerably during the three typical dry years from 20 millimeters in 2001 to as much as 87 millimeters in 1936. More particularly, the shortage of 1949 changes from being a severe water deficit higher than 100 millimeters to an acceptable deficit of around 97 millimeters. However, the water shortage experienced by LNID in 1936 is increased by an additional 24 millimeters, because more of its stored water has to serve the Master Apportionment Agreement to compensate the higher water withdrawals of the WID.

In the case of the water deficits simulated under the Bruce Lake expansion – High Water-use scenario with the Bruce Lake – Current Management model, the magnitude of the water deficits occurring in dry years is also generally decreased except in the case of 2001. Indeed, under these extremely dry conditions the additional water provided through Bruce Lake storage is not sufficient to offset the increased demand of the WID caused by its greater land expansion. Similarly, the shortage in water taking place in 1949 still lays above the threshold value of 100 millimeters as Bruce Lake reservoir cannot compensate the increase in demand caused by the WID's additional land expansion.

Again, it could be concluded that Bruce Lake reservoir increases noticeably the available water supply for the WID, but excessive expansion of the district combined with high water requirements from the crop mix could eventually offset the potential gains.

Table 46: Water Deficits for Three Typical Dry Years for the Current Management – Penalties and Bruce Lake – Current Management models under the High Water-use and the Expansion Bruce Lake – High Water-use Scenario

	1936 Area-Weighted Deficit (mm)				
Irrigation District	**Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**	**Difference with Current**	**Bruce Lake – Current Management – Penalties – Expansion[1]**	**Difference with Current**
WID	196.16	109.5	-86.6	139.6	-56.6
BRID	22.9	22.5	-0.4	23.5	3.9
EID	86.6	86.7	0.1	86.7	0.1
LNID	204.7	228.2	23.5	236.7	32.7
Area-Weighted Total	108.6	104.5	-4.1	110.7	3.3
	1949 Area-Weighted Deficit (mm)				
Irrigation District	**Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**	**Difference with Current**	**Bruce Lake – Current Management – Penalties – Expansion[1]**	**Difference with Current**
WID	153.0	96.9	-56.1	118.5	-31.8
BRID	0.5	0.5	0.0	0.5	0.1
EID	46.8	46.3	-0.5	46.6	-0.2
LNID	60.1	60.1	0.0	60.1	0.0
Area-Weighted Total	48.1	41.6	-6.5	45.3	-2.4
	2001 Area-Weighted Deficit (mm)				
Irrigation District	**Current Management – Penalties**	**Bruce Lake – Current Management – Penalties**	**Difference with Current**	**Bruce Lake – Current Management – Penalties – Expansion[1]**	**Difference with Current**
WID	170.7	151.1	-19.6	182.0	11.4
BRID	22.4	24.4	2.1	24.6	2.3
EID	104.5	103.3	-1.2	103.4	-1.1
LNID	297.3	297.4	0.0	298.5	1.2
Area-Weighted Total	134.2	132.2	-2.0	136.8	2.6

[1] The term *Expansion* indicated that the Expansion Bruce Lake – High Water-use scenario was used as input data instead of the High Water-use scenario

Figure 75 shows the average weekly water deficits for the three typical dry years under the three scenario analysed; the High Water-use scenario simulated by the Current Management – Penalties and the Bruce Lake – Management as well as the Bruce lake Expansion – High Water-use scenario simulated by the Bruce Lake – Current Management. The supply and deficit values are indicated in dam^3 instead of millimeters as the third scenario represents a greater irrigated area; 48,563 hectares compare to 42,493 hectares.

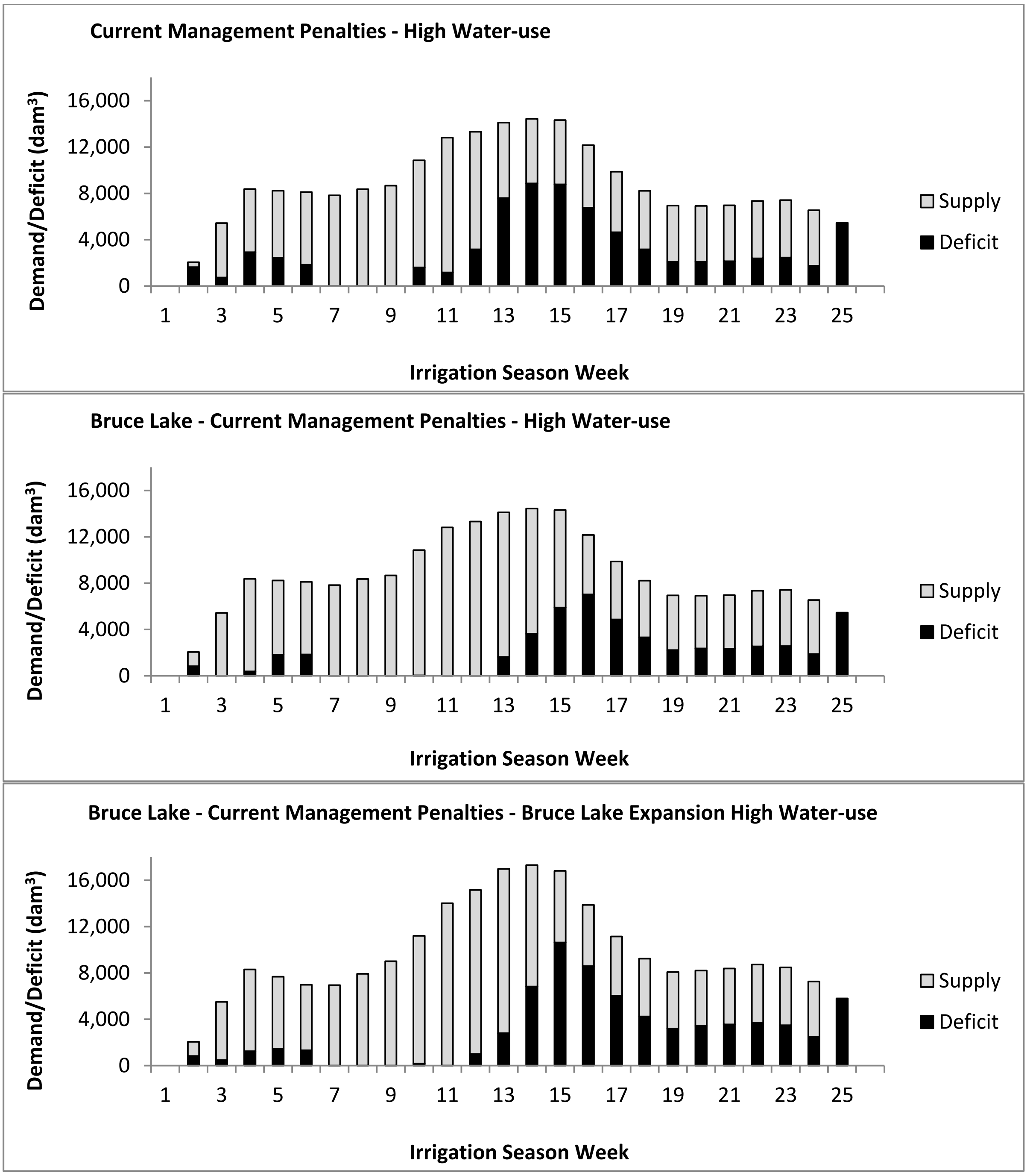


Figure 75: Simulated Weekly Deficits for the WID during Three Typical Dry Year (1936, 1949 and 2001) Simulated by the Current Management – Penalties and Bruce Lake – Current Management – Penalties Models under the High Water-use and Bruce lake Expansion – High Water-use Scenarios

It could be noted that the timing of the water deficits is similar for the three scenarios. However, Bruce Lake reduced the magnitude of the water deficits at the beginning of the season. Furthermore, the additional reservoir permitted to delay the start of the second wave of water deficits occurring in the middle of the irrigation season for the week 13 instead of 10. The magnitude of the second wave of deficits is also reduced when Bruce Lake reservoir is simulated under the High

Water-use scenario but it is not the case under the Bruce Lake Expansion – High Water-use simulation.

5.3.3.4 Master Apportionment Agreement Performances

The Bruce Lake – Current Management model generated similar Master Apportionment Agreement performances compared with the Current Management – Penalties model. Indeed, the three WRMM versions did not success to meet the minimum target of 48% of the natural flow delivered at the Saskatchewan border in the drought of 2001. The Current Management – Penalties version passed 47.18% while the Bruce Lake – Current Management model delivered 47.11% under the High Water-use and 47.10% under the Bruce lake Expansion – High Water-use scenario. Moreover, the percentage of the natural flow crossing the Saskatchewan border was also below 50% for the years 1931 and 1937. On the other hand, the average volume delivered is generally lower when Bruce Lake reservoir is added to WID conveyance system. Indeed, the Bruce Lake – Current Management model decreased the average flow by about 10,000 dam^3 under the High Water-use scenario and by about 16,000 dam^3 when an addition expansion of the land irrigated for the WID is simulated.

5.3.3.5 Lessons Learned

The third objective of the water supply analysis aimed to determine the additional water supply that could be provided through Bruce Lake reservoir under the highest bounding water demand scenarios, particularly for the WID. It was determined that the additional water supply simulated by the Bruce Lake – Current Management version of the WRMM could lower the risks for irrigation of WID under an acceptable level for both the High Water-use and the Bruce lake Expansion – High Water-use scenarios. Indeed, Bruce Lake reservoir permitted to allocate an additional 23,000 dam^3 to WID during dry years but the water supply per unit area could be reduced from 386 to 337 millimeters under the Bruce Lake Expansion – High Water-use scenario as the WID’s irrigated land is further expanded. Therefore, if the construction of Bruce Lake reservoir is combined with a greater expansion of the WID irrigated land than the possible expansion envisioned without the reservoirs, the long-term sustainability of the district could be threatened. The total water supply available under normal to wet conditions simulated with Bruce Lake reservoir remains comparable to those obtained under the WID’s current storage capacity, because the district is less prone to water shortages in normal to surplus years than in dry conditions.

Finally, the work done by Huggard (2014) provides a more extensive analysis of Bruce Lake reservoir benefits for the WID under variable storage capacity and optimization methods.

5.3.4 Water Supply Available under the Lowest Water Demand Scenario

The fourth objective of the water supply analysis aims to quantify the supply available for irrigation under the lowest water demand scenario. It is an unusual practice to use the WRMM model to simulate water demand scenario presenting low risks for irrigation; however, the Alberta Land Institute group is interested in assessing the full spectrum of possible water-use scenarios for a broad range of irrigation development levels. Therefore, the sixth question guiding the results analysis is:

6. How the lowest water-use scenario represented by the Low Waters Uses – Low K_s IDM simulation compares with the Reference Water-use case in terms of water supply available for irrigation?

The quantification of the water supply available to meet the lowest water demand condition is assess by comparing the simulated results generated by the Original WRMM model under the Reference Water-use and the Low Waters Uses – Low K_s input data. It was determined in the section 5.3.1 that the output of the Original WRMM and the Current Management – Penalties version of the WRMM were similar under the Reference Water-use scenario, particularly for dry conditions. Therefore, it is not considered necessary to compare the results obtained from both WRMM versions when assessing the water supply available under unstressed water state.

5.3.4.1 Simulated Water Supply for Dry to Wet Conditions

The Table 47 presents the average water supply available for irrigation during three typical dry years for the Reference and Low Water-use – Low K_s scenarios. The lower water demands caused a reduction of the total area-weighted supply by about 60 millimeters or 224,000 dam^3. It could be noted that the difference in water supply allocated to the WID is small compared to the difference generated for the other districts. Indeed, the WID water supply under the References Water-use scenario was already limited by the district storage capacity, particularly in dry years. Therefore, the water supply allocated to the WID under the Low Water-use – Low K_s scenario, which is driven by lower water demands remains closer to the one constrained by physical limits.

Table 47: Water Supply for Three Average Dry Years (1936, 1949 and 2001) Simulated by the Original WRMM under the Reference and High Water-use Conditions

	Reference Water-use	Low Water-use	
Irrigation District	**Original WRMM (mm)**	**Original WRMM (mm)**	**Difference with Reference (dam^3)**
WID	329.1	309.9	-7,357
BRID	457.4	399.6	-60,804
EID	457.8	365.7	-115,907
LNID	293.5	249.9	-40,112
Area-Weighted Total	402.2	340.2	-224,181

Table 48 presents the normal year results, which generated greater disparities between the two water-use scenarios. Indeed, the area-weighted water supplied to the four districts is decreased by about 110 millimeters or 403,000 dam^3, which is equivalent to about 19% of the four district maximum water licence allocation (2,102,900 dam^3). Again, some districts experienced higher water supply reductions compared to others, as a consequence of their previous water supply limitations and their respective water demand decreases whose are driven by various crop mix and evapotranspiration scaling factors under the Low Water-use – Low K_s scenario.

Table 48: Water Supply for Three Average Normal Years (1959, 1962 and 1964) Simulated by the Original WRMM under the Reference and High Water-use Conditions

	Reference Water-use	Low Water-use	
Irrigation District	**Original WRMM (mm)**	**Original WRMM (mm)**	**Difference with Reference (dam^3)**
WID	307.6	228.2	-30,542
BRID	345.9	287.3	-61,714
EID	381.1	244.9	-171,333
LNID	318.1	166.5	-139,291
Area-Weighted Total	347.0	235.5	-402,880

The Table 49 presents the wet years average water supply values. In this case the total water supply changed from 269 to 174 millimeters, which is a reduction of about 343,000 dam^3.

Table 49: Water Supply for Three Average Wet Years (1954, 1965 and 1981) Simulated by the Original WRMM under the Reference and High Water-use Conditions

	Reference Water-use	Low Water-use	
Irrigation District	**Original WRMM (mm)**	**Original WRMM (mm)**	**Difference with Reference (dam^3)**
WID	209.8	146.5	-24,340
BRID	280.8	228.7	-54,837
EID	296.5	178.8	-148,089
LNID	241.6	115.4	-115,892
Area-Weighted Total	268.7	173.8	-343,158

5.3.4.2 Risk Measures for the Water Deficits

The risk measures of the water deficits simulated under the Reference Water-use and the Low Water – Low K_s scenarios by the Original WRMM are presented in table 50. The performances of all the districts are improved to near perfect results when the water demands are lowered to represent a crop mix having lower water requirement and smaller evapotranspiration scaling factors. Indeed, only low levels of risk for water deficits are expected in terms of the districts reliability, resiliency and vulnerability.

Table 50 : Risk Measures of the Water Deficits (1928-2001) for the Original WRMM under the Reference Water-use and Low Water-use Conditions

	Reliability		Resilience		Vulnerability	
Irrigation District	**Reference Water-use**	**Low Water-use**	**Reference Water-use**	**Low Water-use**	**Reference Water-use**	**Low Water-use**
WID	0.95	1.00	1.00	1.00	36.93	0.74
BRID	1.00	1.00	1.00	1.00	0.00	0.00
EID	0.98	1.00	0.85	1.00	20.64	0.00
LNID	0.93	1.00	1.00	1.00	57.40	0.00
Area-Weighted Total	0.97	1.00	0.95	1.00	25.71	0.08

5.3.4.3 Typical Dry Year Water Deficits

The difference in the magnitude of water deficits occurring in three typical dry years is compared for both water-use scenarios in Table 51. Under the Low Water-use – Low K_s scenario all the water shortages simulated fall below the threshold value of 100 mm as oppose to the results generated under the Reference Water-use case. Even the severe drought of 2001 generates acceptable water deficits for the most vulnerable districts; the WID and the LNID.

Table 51: Water Deficits for Three Typical Dry Years for the Original WRMM under the Reference and High Water-use Conditions

	1936 Area-Weighted Deficit (mm)			1949 Area-Weighted Deficit (mm)			2001 Area-Weighted Deficit (mm)		
Irrigation District	**Reference Water-use**	**Low Water-use**	**Diff. with Reference**	**Reference Water-use**	**Low Water-use**	**Diff. with Reference**	**Reference Water-use**	**Low Water-use**	**Diff. with Reference**
WID	166.4	90.9	-75.5	93.1	16.2	-76.9	126.0	46.3	-79.7
BRID	3.7	0.0	-3.7	0.2	0.1	-0.1	25.3	0.1	-25.2
EID	86.3	15.3	-70.9	44.2	0.2	-44.0	73.9	0.0	-73.9
LNID	145.3	5.9	-139.5	27.2	0.0	-27.2	251.0	29.3	-221.7
Total	85.8	16.5	-69.3	32.3	1.8	-30.5	110.3	12.4	-97.9

5.3.4.4 Master Apportionment Agreement Performances

The Master Apportionment Agreement performances are improved under the reduced water demand scenario. Indeed, the average percentage of the natural flow delivered to the Saskatchewan is increased from 61.30% to 65%. More interestingly, the Original WRMM simulation for the Low Water-use – Low Ks scenario succeed to pass more than 50% of the natural flow over the length of the study period, and even during the 2001's drought. It was not the case under the Reference Water-use, which delivered 48.95% of the natural flow in 1931 and 49.19% in 2001.

5.3.4.5 BRID's Diversion Rates

The weekly diversion rates of the BRID for the two water-use scenarios analysed are presented in Figure 76. The lower demand simulated produces similar diversion rate as the reference case at the beginning of the season and during the month of July until mid-August (weeks 27 to 32). For the remaining part of the summer, the diversion rates are reduced as the water demand to supply is lower. Interestingly, even if the BRID's irrigation demand is considerably lowered, the diversion rate in the critical months of July and August remain relatively similar to those simulated by the current water demand, because the model aims to maintain the reservoirs close to their ideal levels under STO mode.

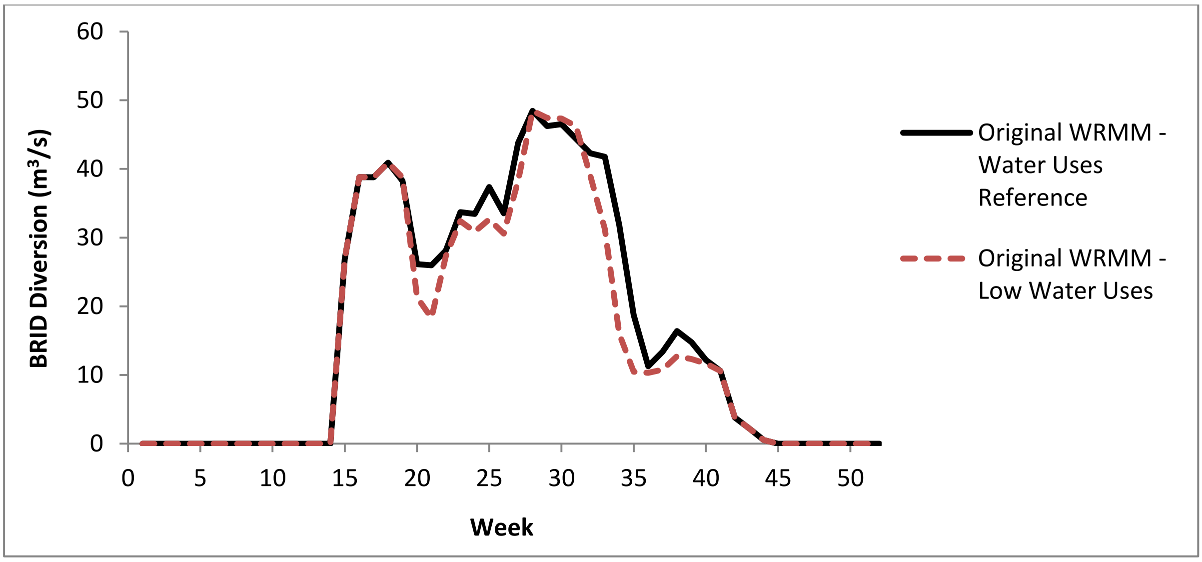


Figure 76: BRID's Average Weekly Diversion Rate in Carseland Canal for Three Typical Normal Years Simulated by the Original WRMM under the Reference and Low Water-use Conditions

5.3.4.6 Lessons Learned

The fourth objective of the water supply analysis was to quantify the water available for irrigation under the lowest water-use scenario and how it compares with the reference case. It was determined that the Low Water-use – Low K_s scenario of irrigation development generated water supply per unit area of about 60 to 110 millimeters below the Reference Water-use scenario. In fact, the area-weighted water supply available for the four districts varies for dry to wet conditions from 270 to 400 millimeters in the case of the Reference Water-use scenario and from as low as 174 millimeters to 340 millimeters in the case of the Low Water-use – Low K_s scenario using the Original WRMM model. The risk measures of the water deficits, the Master Apportionment Agreement performances as well as the diversion rate in Carseland canal were all improved by the low water-use condition which reduced the water pressure on the system.

6. Conclusion and Recommendations

6.1 Conclusion

The irrigation sector is facing the challenges of coping with increasing food demand, climate change impacts and ecological concerns (Lenton 2014; Martz *et al.* 2007). Irrigation is at the heart of the southern Alberta landscape, enhancing rural community development and ensuring agricultural industry sustainability, but accounts for the greatest water-use of Alberta's heavily-allocated South Saskatchewan River Basin. To reduce the pressure on the limited water resources, the Government of Alberta restricted the use of unallocated water to conservation, storage or First Nations projects for the Bow, Oldman and South Saskatchewan Sub-basins of the SSRB, enforcing the need to optimize water-use in irrigation (SWSSSC 2010). Water resources modelling studies have been conducted to assess the effects of changing supply and demand in the SSRB and to improve water management for sound environmental, economic and social needs. However, despite progress in reservoir model capabilities, decision-makers and reservoir managers still resist application of the output of these computer-based models to real-world reservoir operations (Labadie 2004, Loucks 2005, Simonovic 1992, Wurbs 1993, Yeh 1985, Toebes & Ruvikchai 1978).

The main objective of this research was therefore to understand and improve reservoir management strategies for sustainable development of the irrigation sector. To achieve this, the study firstly aimed to bridge the gap between the theory and practice of water resources modelling studies by assessing how the fundamental behaviour of optimization models relates to real-world management. The methodology used was innovative in the sense that it applies a qualitative interview approach to collect information from water managers including the data they rely on and their processes for decision-making for reservoir operations. Analysis of the reservoir managers' operational decision-making under different hydrological conditions was undertaken through visits and interviews in the main irrigation districts in the SSRB. The results suggest that the rules behind water allocations in Alberta should be oriented toward 1) basin-scale cooperation, since the districts negotiate their diversions with one another and do not strictly apply the seniority principle on water rights, 2) accounting for the effects of early-season water rationing, which involves on-farm water demand reductions by irrigators and is based on data from the snow pillow survey, reservoir winter storage, soil moisture and average precipitation volume, and 3) with reservations as to its practicality and applicability, consideration of day-by-day release strategies if modelling capacity and data availability permit the optimization of water allocations on a daily time-scale. The real-world data contributed to a better understanding of water managers' perspectives that may lead to more valuable outcomes from modelling studies, and results that may be more readily adopted by water managers. Note that the findings might be unique to Western Canadian, particularly in terms of sharing the water shortages through river basin-scale cooperation, the bi-seasonality in reservoir operating rules and the dependency of water supply availability on snowpack accumulations. However, application to other regions of the world of the methodology developed for this study, which was based on the qualitative research theory, has a great potential to help modellers to understand water managers' perspectives from various political and geographical contexts.

Based on the previously described analysis of the basis of reservoir managers' operational decisions, it was possible to address the second objective of this research, which was to evaluate whether water availability in the Bow River Basin could be increased by improving reservoir management. Assessment of the benefits of alternative reservoir management strategies applied in the Bow River Irrigation District (BRID) for the water supply available to the three irrigation districts of the Bow River Basin, the WID, BRID and EID, as well as the LNID of the Oldman River Basin was done through the use of the Water Resources Management Model (WRMM) of AEP. Previous modelling studies applied to the SSRB generally addressed the river system state under "what if" scenarios of water demands or allocation policies, but only a few have investigated reservoir operations of the existing infrastructure by optimization models. It was observed that modifying the WRMM model to represent the BRID's current operating rules as a result of bank erosion, flood mitigation and other changes in operational practices only marginally affected the water supply available in the Bow River Basin. However, when the real dead storage level served as the minimum operating zone of McGregor Reservoir, rather than the artificially high level simulated in the original WRMM, the BRID water supply is overall increased in dry years and even in consecutive dry years. However, because McGregor Reservoir is drawn down lower than the elevation at which some irrigators experience diversion difficulties, the water deficits of BRID's Block 339, which represents the irrigators who divert water directly from McGregor Reservoir storage, reached severe magnitudes frequently along the study period. The downside of simulating the real McGregor storage for Block 339 was mitigated by inverting the penalties associated with the BRID reservoir operating zones as suggested by the literature for reservoirs in series. Under this inverse penalty scheme, which forced the model to empty and refill the BRID's downstream reservoirs first and McGregor reservoir last, the BRID performance was improved. Finally, new rule curves favouring drought mitigation were modelled for the BRID's external reservoirs. Even if the deficit performances were slightly improved for all the districts under this scenario, the gains in water supply were observed mainly for the BRID and particularly for its more vulnerable irrigation block (Block 339) and they were not sufficient to mitigate drought impacts significantly compared to the current management practices. Most importantly, because the BRID is already in a good position in terms of water security, all the simulated reservoir management alternatives only marginally affected the performance of the risk measures related to water deficits, the water available for the other irrigation districts, the Master Apportionment Agreement and the diversion rate from the Bow River. As a result, the original WRMM and the modified versions of the WRMM led to similar conclusions for irrigation planning management studies.

From the reservoir management modelling work conducted to address the second objective, two reservoir management strategies were selected for their ability to maximise the water supply available for irrigation purpose and to permit assessment of the risks and trade-offs anticipated for the next 25 years (2040) associated with irrigation sector development in the Bow River Basin area – the third goal of the research study. More specifically, the Original WRMM and the Current Management – Penalty scenarios were used to establish the water supply limits for the three irrigation districts of the Bow River Basin and the LNID under minimum and maximum irrigation demand levels and for dry to wet conditions. The simulation of the effect of Bruce Lake Reservoir was lastly analysed in order to assess water availability for the WID under a broader range of water storage options. The simulation work was made possible through the use of the Irrigation Demand Model of AAF in conjunction with the WRMM. The modification of the irrigation districts' expansion limits, crop mixes and the evapotranspiration scaling factor in the IDM were partly based on the interview data collected and partly based on suggestions from ALI and AAF staff. The changes in parameter values helped to produce bounding scenarios of irrigation demands.

The Reference Water-use scenario resulted in an average irrigation demand of 347 mm per unit area (1,259,000 dam^3) whereas the highest irrigation demand (Expansion – High Water-use scenario) reached 389 mm per unit area (1,466,000 dam^3) as well as 386 mm (1,478,000 dam^3), when Bruce Lake Reservoir would permit an additional expansion of the WID (Bruce Lake Expansion – High Water-use scenario), and finally, the lowest irrigation demand (Low Water-use – Low Target scenario) was about 237 mm per unit area (857,000 dam^3). By applying the various water-use scenarios to the WRMM, it was determined that the area-weighted water supply available for the four districts varies for dry to wet conditions from 270 to 400 millimeters in the case of the current water-use, 300 to 410 millimeters under the highest water demands scenario when the original WRMM version is used and could increase to 430 mm in dry years under the modified WRMM representing BRID current reservoir management, McGregor total storage and an inverse penalty scheme, and finally, as low as 170 millimeters to 340 millimeters in the case of the lowest irrigation demands. More particularly, the water shortage risks associated with the reference water-use and the low water-use scenarios were below acceptable levels for the four irrigation districts. However, the high water-use scenario is not sustainable in terms of meeting the Master Apportionment Agreement requirements and for both the LNID and the WID in terms of water supply reliability. The yearly water deficits simulated for these districts are greater than 100 millimeters in more than 10% of the years simulated. Bruce Lake reservoir permitted the allocation of an additional 23,000 dam^3 to the WID during dry years but the water supply per unit area could be reduced from 386 to 337 millimeters when the district irrigated area is expanded further. The additional water supply provided by Bruce Lake could still lower the risks for irrigation of the WID to an acceptable level, considering both expansion scenarios.

6.2 Recommendations

As a consequence of the current limitations of the WRMM, it was not possible to apply the MTO technique to analyse the reservoir operations of the BRID. The simpler STO simulation only permitted evaluation of the performance of the original rule-curves and a limited number of user-defined rule-curve alternatives. Under the STO simulation, these rigid reservoir rule-curves constrain the water allocations as the optimization algorithm cannot deviate significantly from them. As a result, the reservoir release solutions generated by the WRMM are probably sub-optimal, particularly in the context of variable water supply. Indeed, the need for developing adaptive water management strategies in order to cope with the uncertainty of future inflows has been identified by various studies (EPSMWALC 2013; Hill et al. 2013; Ilich 2011; IWMSC 2002a). The concept of finding the optimum policy resilient to a series of possible future scenarios would not be as appropriate as finding dynamic adaptive strategies, which could be inferred by MTO solutions analysis.

The value of trying different user-defined rule curves through STO modelling work still permitted evaluation of the relative impact for different components of the river basin system of changing reservoir operating rules. For example, changing the reservoir operating levels in the BRID did not affect significantly the other districts' river diversions, but had a greater impact on its own irrigation blocks. Further simulations of reservoir operation changes for the other districts located in the Bow River Basin area through the STO analysis might lead to different conclusions, which can be useful to determine which of the reservoirs should be optimized first in order to produce the greatest benefit for the entire river basin system. However, the cumbersome work required to compare various changes in operating guidelines of the reservoirs assessed leads to reservations about the value and practicality of the STO modelling work applied to address reservoir management options. The STO approach is valuable in comparing changes in reservoir storage availability (the addition of Bruce Lake Reservoir in the WID for example) or the impact of increasing irrigation demands (such as the third objective addressed in the thesis work), rather than for developing "optimized" reservoir operating curves.

Of additional importance is the fact that the presented modelling work was based on historical observations, which may not be representative of future water supply and demand due to the non-stationarity of hydrological and climatic conditions from the effect of climate change (Milly *et al.* 2005; Rood *et al.* 2008); thus, underestimating the risks for the irrigation sector management.

Finally, the current network-flow programming formulation used in the WRMM leads to mass balance problems and inaccurate consideration of non-network constraints (Ilich 2008; 2009; AESRD 2010). The accuracy of results could thus be improved by the use of more advanced optimization algorithms.

Therefore, further research on reservoir operations in Alberta should focus on the following areas:

- Applying MTO models to water allocation in the SSRB in order to derive dynamic operating rules applicable in daily to weekly operations of reservoir for optimal water-uses at a basin-scale level;
- Evaluating the robustness of various reservoir management alternatives under changing water supply and demand scenarios to cope better with future water availability challenges and climate-related non-stationarity;
- Simulating and optimizing water allocations in the SSRB by the use of more accurate river basin management models than the original WRMM whose modelling capacities are limited by the optimization solver used in the network flow programming formulation of the system.

6.3 Additional Reflections

The research work presented and the recommendations that followed were based on the assumption that by improving water-use efficiency through better management of reservoir operations, water savings could help irrigators to cope with increasing water demand for irrigation and indirectly for food production, while maintaining the integrity of the environment. In other words, this research mainly focused on the water supply aspect of a holistic water management theory that integrates socio-economic and environmental water needs. In addition, academia and society in general should reflect more on the impact of consumer choices on natural resources availability and integrity and how can we minimize our environmental footprint, thus addressing the water demand aspect. Global behavioural changes regarding food consumption and production would allow water savings and environmental service enhancements in another order of magnitude than the changes achievable through reservoir management (Yang & Cui 2014). For example, meat production considerably increases the pressure on water resources and land uses. As a comparison, producing 1 kg of meat necessitates about 70 times more water than producing the same mass of vegetables (UNDESA, 2013). The United Nations further reported that feeding one person for a year requires from 1,000 to 3,000 tonnes of water according to his or her personal diet (UNW-DPAC, 2011), a range that highlights the importance of assessing the global sustainability of our food habits.

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Appendix A – Interview Questions

Table 52: Interview Questions Developed for Understanding Water Manager's Perspective on Reservoir Management

1	**Water network specifications**
1.1	How many diversion points does the district use? What are the possible diversion volumes (flow rates) at these points? For example, how do the diversion structures impose restrictions on inflow rates?
1.2	Can you please explain the water license conditions as specified by AESRD? Are there particular dates to respect for District diversions and are the dates flexible?
1.3	*Addressed to BRID only:* What are the maximum and minimum operating levels of each reservoir and structure?
1.4	What are the physical constraints of the network influencing the water diversion(s)? What is the necessary charge of water within the main components of the water conveyance network to sustain flow?
1.5	What are the times-of-travel for water in the major canals in the system? How variable are they over an irrigation season, and what determines their variability? How do you take the times-of-travel into account in responding to producer demands for water?
1.6	What are the conditions in the reservoirs and canals at the beginning and end of a growing season (empty, full …)? Can you explain why they are in such condition?
1.7	Are there any conditions that could make you either fill or empty the reservoirs at the end of the growing season? Who decides on the final condition of the reservoir, the District or AESRD?
1.8	If the canals are all empty at the end of the growing season, how/when does the flushing process take place?
2	**General water management strategy**
2.1	Do you ever coordinate withdrawal timing with other irrigation districts? If so, why? For example, can you/do you collaborate with other districts to meet irrigator requirements in your districts, while minimizing total daily/weekly withdrawals from the river?
2.2	Do you always apply First In Time, First In Right (FITFIR), or are there conditions that would cause you to deviate from FITFIR? What are these conditions? How do you decide whether they apply? For example, do you deviate from FITFIR in drought conditions?
2.3	What are your operating rules/rules of thumb used to manage each reservoir (ex: Ideal reservoir level over the year, refill and drawn down schedule, amount of released water based on weather forecast, etc…)? Do they differ if the reservoir is on-stream or off-stream?
2.4	What information do you use to help you know when to release or when not to release water? (Water demands from irrigator, forecasted weather, hydrological surveys…)
2.5	What sorts of hydrological, irrigation system, crop-related, and other data do you collect and rely on? What is the timescale at which these data are collected, and at which they are useful?
2.6	*a) If the question is addressed to the Irrigation Districts:* Does the way reservoirs are operated by Alberta Government influence your reservoir operations? How do you coordinate your work with them? *b) If the question is addressed to the Government of Alberta:* Does the way reservoirs are operated by the irrigation districts influence your reservoir operations? How do you coordinate your work with them?
2.7	Have you changed your operating rules over the years? If yes, why were they changed, how were they changed, and when were they changed? Have the changes been effective?
2.8	What are your biggest challenges in managing the reservoir and conveyance system for irrigation and other purposes? How do these challenges constrain your system management?

3	**Water management strategies for reservoirs with different purposes**
3.1	Is there more than one type of reservoir in the system? What are they, and how do they differ from one another? Are any of the reservoirs managed for multiple uses, and if so, how does that affect operations and water-use priorities?
3.2	Have the reservoir purposes or management strategies changed over the years? If yes, what caused the changes, and when? How have the changes affected your operating rules?
3.3	What indicators do you use to meet other reservoir purposes (if applicable)? (Ex: Water level required for recreational use, or for municipal/domestic uses)
3.4	What priority do you use between environmental, recreational, livestock, and irrigation requirements? Do those priorities depend on the time of year, and do they remain the same during water shortages?
4	**Water management strategy under different climatic conditions**
4.1	How do you deal with dry year, wet year, and normal hydrological year? Do you normally distinguish between different "types of hydrological years"? E.g. are there any general "rules of thumb" you apply to the overall system, or to individual reservoirs? Are these "rules of thumb" different in dry vs. wet years?
4.2	What are the factors that make you believe you are facing a dry year, wet year, or normal hydrological year?
4.3	Are the operating rules adjusted at the beginning of the irrigation season and/or over the irrigation season, or do they remain constant within a year and from year-to-year?
4.4	Are the operating rules different in times of water shortage?
4.5	During a drought, can you inform the irrigators at the beginning of the season so they can adjust their crop patterns or do temporary water license transfers? Can you/do you forecast a drought year?
4.6	During a drought, how do you manage the deficit over the growing season? Is the deficit more or less distributed equally over the season or are other strategies applied?
4.7	What is your definition of water deficit?
4.8	Do you have an example of a year that was particularly well-managed, even in dry/difficult conditions? What happened that year, and why was it particularly good?
4.9	Do you have an example of the opposite? I.e. a year that was not well-managed? Why was the system not well-managed that year?
5	**Water management tools**
5.1	Do you use any software/hardware tools to help you manage the reservoir system? What do you like or not like about these tools?
5.2	Have you seen WRMM results in the past, and were they of any use? Are the results of the BRPC study any different?
6	**Future trends**
6.1	Do you think irrigators are interested in saving more water by improving water efficiency, or would external incentives be necessary?
6.2	Do you think there is an interest in expanding the irrigated area in your District? How close are the plebiscites in general? Does the District play an active role in promoting expansion?
6.3	If the growing season lasted longer because of warmer temperature, how do you think this change would affect crop patterns and irrigation? Do you think irrigators would be interested in trying to grow different crops?
7	**Final comments**
7.1	Are there components of the research that would be useful for you? Are there extensions to the proposed work that you could recommend?
7.2	Would you be willing to participate in future water systems management studies?
7.3	Do you have any other recommendations or comments?

Appendix B – Reservoir Operating Zone Inverse Penalties Developed for the WRMM

Table 53: BRID's Reservoir Zone Penalties in the Updated Ideal Curves – Penalties and in the Current Management – Penalties Versions

Updated Ideal Curves – Penalties					
Reservoir	**Second Zone Above Ideal Curve**	**First Zone Above Ideal Curve**	**First Zone Below Ideal Curve**	**Second Zone Below Ideal Curve**	**Third Zone Below Ideal Curve**
McGregor	4 600	9 500	100	1 175	10 000
Travers-Little Bow	4 600	9 500	20	1 000	10 000
Badger		10 000	1	10 000	
Scope		10 000	1	10 000	
Lost Lake		10 000	1 180	10 000	
Block 339			1 240		
Current Management – Penalties					
Reservoir	**Second Zone Above Ideal Curve**	**First Zone Above Ideal Curve**	**First Zone Below Ideal Curve**	**Second Zone Below Ideal Curve**	**Third Zone Below Ideal Curve**
McGregor	4 600	9 500	100	1 175	10 000
Travers-Little Bow	4 600	9 500	20	1 000	10 000
Badger		10 000	1	10 000	
Scope		10 000	1	10 000	
Lost Lake		10 000	1 180	10 000	
Block 339			1 170		

Appendix C – Additional IDM Simulations Data

Table 54: IDM's Crop Mixes Input Data for the Reference, High Water-use and Low Water-use Scenarios for the Current Expansion Limit (hectares)

		2012's Crop Mix				High Water-use Crop Mix				Low Water-use Crop Mix			
Crop type	Crops	WID	BRID	EID	LNID	WID	BRID	EID	LNID	WID	BRID	EID	LNID
CEREALS	Barley	7909	8505	5790	9817	5300	7797	8505	9817	4248	6825	6590	9111
	CPS Wheat	158	819	1994	610	1994	158	819	610	1117	158	819	610
	Durum Wheat	2948	146		3398		2948	146	3398		2948	146	2636
	Grain Corn	2887	686		392		2887	686	392		1917	439	392
	Hard Spring Wheat	23496	18782	1773	5166	1773	17368	18128	4657	1190	17393	11598	5166
	Malt Barley		321		159			220	159			321	5951
	Oats	115	688	159	327	159	115	625	183	159	115	688	327
	Rye	76	67		739		76	67	535		76	67	739
	Soft Wheat	2133	323	168	215	168	2133	323	215	168	2133	323	215
	Triticale	69	1582		440		69	1582	440		69	1041	364
	Winter Wheat	1367	388	588	226	588	1367	388	226	300	1367	388	226
	Total (hectare)	41158	32305	10471	21488	9981	34918	31489	20630	7183	33000	22418	25736
FORAGES	Alfalfa - Two cuts	2081	14025	4909	7028	10490	9888	29531	19396	2486	1190	7068	4334
	Alfalfa - Three cuts	539	1428		303		4252		57		345	933	303
	Alfalfa Hay	3694	1720	1945	4390	190	12197	2233	3461	979	1888	992	3323
	Alfalfa Silage		1507		2390				205			1002	1639
	Barley Silage	1322	1829	2045	20313	1532	1322	1829	15417	5255	1322	1829	21949
	Barley Silage (underseeded)		87	67	314	67		87	314	67		87	231
	Brome Hay	1031		87	473	87	1031		473	87	518		391
	Corn Silage	2736	5745	358	11730	358	2736	5745	11730	257	2010	2950	7878
	Grass Hay	995	4046	1448	2010	1448	995	4046	2010	820	833	2172	1663
	Green Feed	636	1633	10	110	10	541	1370	110	2016	8228	21272	2193

	Milk Vetch				73				73				73
	Millet												
	Native Pasture	1001	502	1127	158	1127	1001	502	158	582	616	384	158
	Oats Silage		41					41				41	
	Tame Pasture			1756	2763	1561	3392	17663	2327	1756	4859	19313	2763
	Timothy Hay	4935	19892	314	2745	314	732	427	2745	194	394	427	1651
	Tritcale Silage	732	427										
	Total (hectare)	19701	52882	14067	54800	17185	38088	63474	58475	14498	22203	58472	48548
OIL SEEDS	Canola	17521	21505	10082	11176	7632	9121	13141	8358	10082	9396	21505	10430
	Flax	2344	4755		653		1655	4163	653		10470	4655	653
	Mustard	190			42		190		42		190		42
	Safflower				82				82				82
	Total (hectare)	20056	26260	10082	11953	7632	10965	17305	9135	10082	20056	26161	11207
SPECIALTY	Alfalfa Seed	2737	6528		77		2737	6528	77		1537	3352	77
	Canola Seed												
	Carrots		73					73				2258	
	Dill		53		77			53	77			53	77
	Dry Beans	5279	1379		199		2770	838			3572	7991	
	Dry Peas	2067	1263	616		440	1648	985	199	3663	3161	1263	3361
	Faba Beans	683	66				683	66			683	66	
	Fresh Corn (sweet)	62	4				62	4			62	4	
	Fresh Peas	719					590				13233		
	Grass Seed	233	19		159		233	19	159		233	19	83
	Hemp												
	Lawn Turf			1929	398	1929			398	1929			398
	Lentils		28					28				28	
	Market Gardens	25	40	41	25	41	25	40	25	41	25	40	25
	Mint	222	587				222	587			222	587	
	Nursery	4	177	579	4	579	4	177	4	579	4	177	4
	Potatoes	5343	1808		550		5343	1808	550		3130	1152	355
	Seed Potatoes		424	378		378		424		189		232	

	Soybeans												
	Sugar Beets	6320	435		1475		6320	435	1475		3551	370	1335
	Sunflower	356	1082		87		356	1082	87		293	771	87
	Total (hectare)	24051	13967	3543	3051	3367	20994	13148	3051	6401	29706	18365	5801
OTHER	Miscellaneous	15	84	281	573	281	15	84	573	281	15	84	573
	Summer Fallow	241	361				241	361			241	361	
	Total (hectare)	255	445	281	573	281	255	445	573	281	255	445	573
	Grand Total (hectare)	38446	105221	125860	91865	38446	105221	125860	91865	38446	105221	125860	91865

Table 55: IDM's Crop Mix Input Data for the Expansion, High Water-use – Expansion and Low Water-use – Expansion Scenarios (hectares)

		2012's Crop Mix				**High Water-use Crop Mix**				**Low Water-use Crop Mix**			
Crop type	**Crops**	**WID**	**BRID**	**EID**	**LNID**	**WID**	**BRID**	**EID**	**LNID**	**WID**	**BRID**	**EID**	**LNID**
CEREALS	Barley	8517	8751	6399	9817	5858	8397	8751	9817	4695	7350	6781	9111
	CPS Wheat	170	842	2204	610	2204	170	842	610	1235	170	842	610
	Durum Wheat	3174	150		3398		3174	150	3398		3174	150	2636
	Grain Corn	3109	706		392		3109	706	392		2064	452	392
	Hard Spring Wheat	25304	19325	1959	5166	1959	18704	18653	4657	1315	18730	11933	5166
	Malt Barley		330		159			226	159			330	5951
	Oats	124	707	176	327	176	124	643	183	176	124	707	327
	Rye	82	69		739		82	69	535		82	69	739
	Soft Wheat	2298	332	186	215	186	2298	332	215	186	2298	332	215
	Triticale	75	1628		440		75	1628	440		75	1071	364
	Winter Wheat	1472	399	649	226	649	1472	399	226	332	1472	399	226
	Total (hectare)	44324	33240	11574	21488	11032	37604	32400	20630	7939	35538	23067	25736
FORAGES	Alfalfa - Two cuts	2241	14431	5426	7028	11594	10649	30386	19396	2748	1281	7273	4334
	Alfalfa - Three cuts	581	1469		303		4579		57		372	960	303
	Alfalfa Hay	3978	1770	2150	4390	210	13135	2297	3461	1082	2033	1020	3323
	Alfalfa Silage		1551		2390				205			1031	1639

	Barley Silage	1424	1882	2261	20313	1694	1424	1882	15417	5808	1424	1882	21949
	Barley Silage (underseeded)		90	74	314	74		90	314	74		90	231
	Brome Hay	1110		96	473	96	1110		473	96	558		391
	Corn Silage	2946	5911	396	11730	396	2946	5911	11730	284	2164	3035	7878
	Grass Hay	1071	4163	1601	2010	1601	1071	4163	2010	907	897	2235	1663
	Green Feed	685	1680	11	110	11	583	1409	110	2228	8861	21887	2193
	Milk Vetch				73				73				73
	Millet												
	Native Pasture	1078	516	1246	158	1246	1078	516	158	643	663	396	158
	Oats Silage		43					43				43	
	Tame Pasture			1941	2763	1725	3653	18174	2327	1941	5233	19872	2763
	Timothy Hay	5315	20467	348	2745	348	788	439	2745	215	424	439	1651
	Tritcale Silage	788	439										
	Total (hectare)	21217	54413	15548	54800	18994	41017	65311	58475	16024	23911	60164	48548
OIL SEEDS	Canola	18869	22128	11144	11176	8435	9822	13522	8358	11144	10119	22128	10430
	Flax	2525	4892		653		1782	4284	653		11275	4790	653
	Mustard	205			42		205		42		205		42
	Safflower				82				82				82
	Total (hectare)	21599	27020	11144	11953	8435	11809	17806	9135	11144	21599	26918	11207
SPECIALTY	Alfalfa Seed	2948	6717		77		2948	6717	77		1656	3449	77
	Canola Seed												
	Carrots		76					76				2324	
	Dill		55		77			55	77			55	77
	Dry Beans	5685	1419		199		2984	862			3847	8223	
	Dry Peas	2226	1300	681		486	1775	1014	199	4049	3404	1300	3361
	Faba Beans	736	68				736	68			736	68	
	Fresh Corn (sweet)	67	4				67	4			67	4	
	Fresh Peas	774					636				14251		
	Grass Seed	251	19		159		251	19	159		251	19	83
	Hemp												

	Lawn Turf			2132	398	2132			398	2132			398
	Lentils		29					29				29	
	Market Gardens	27	41	46	25	46	27	41	25	46	27	41	25
	Mint	239	604				239	604			239	604	
	Nursery	4	182	640	4	640	4	182	4	640	4	182	4
	Potatoes	5754	1861		550		5754	1861	550		3371	1185	355
	Seed Potatoes		436	418		418		436		209		239	
	Soybeans												
	Sugar Beets	6806	448		1475		6806	448	1475	0	3824	381	1335
	Sunflower	383	1113		87		383	1113	87	0	315	794	87
	Total (hectare)	25901	14372	3916	3051	3721	22609	13528	3051	7075	31992	18896	5801
OTHER	Miscellaneous	16	86	311	573	311	16	86	573	311	16	86	573
	Summer Fallow	259	372				259	372			259	372	
	Total (hectare)	275	458	311	573	311	275	458	573	311	275	458	573
	Grand Total (hectare)	42493	113315	129503	91865	42493	113315	129503	91865	42493	113315	129503	91865

Table 56: Ideal Irrigation Demands Results for all IDM Scenarios

Actual Expansion Limit		**2012's Crop Mix - Ks =90%**					**Low Water-use Crop Mix - Ks =90%**					**High Water-use Crop Mix - Ks =90%**				
Irrigation District	Total Area	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation
	(ha)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)
WID	38 446	321	-	123 319	-	77	290	-9.55	111 545	-9.55	73	350	9.10	134 542	9.10	80
BRID	105 221	346	-	364 050	-	71	324	-6.45	340 571	-6.45	69	399	15.38	420 048	15.38	75
LNID	91 865	304	-	279 422	-	78	288	-5.34	264 496	-5.34	76	338	11.07	310 348	11.07	81
EID	125 860	391	-	492 010	-	82	350	-10.43	440 688	-10.43	78	427	9.23	537 415	9.23	84
Area-Weighted Total	361 393	348	-	1 258 801	-	72	320	-8.06	1 157 300	-8.06	70	388	11.40	1 402 354	11.40	76
Future Expansion Limit		**2012's Crop Mix - Ks =90%**					**Low Water-use Crop Mix - Ks =90%**					**High Water-use Crop Mix - Ks =90%**				
Irrigation District	Total Area	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation
	(ha)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)
WID	42 493	316	-1.4	134 367	9.0	77	286	-10.98	121 338	-1.61	73	360	12.19	152 913	24.0	24.00
BRID	113 315	344	-0.5	390 187	7.2	71	322	-7.02	364 543	0.14	69	397	14.83	450 209	23.7	23.67
LNID	91 865	304	0.0	279 422	0.0	78	288	-5.34	264 496	-5.34	76	338	11.07	310 348	11.1	11.07
EID	129 503	390	-0.2	505 264	2.7	81	350	-10.59	452 615	-8.01	78	427	9.11	552 360	12.3	12.27
Area-Weighted Total	377 176	347	-0.3	1 309 240	4.0	72	319	-8.43	1 202 992	-4.43	70	389	11.57	1 465 831	16.4	16.45
Future Expansion Limit with Bruce Lake		**2012's Crop Mix - Ks =90%**					**Low Water-use Crop Mix - Ks =90%**					**High Water-use Crop Mix - Ks =90%**				
Irrigation District	Total Area	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation
	(ha)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)
WID	48 563	311	-3.0	151 129	22.6	77	280	-12.60	136 143	10.40	73	340	6.10	165 266	34.01	80
BRID	113 315	344	-0.5	390 187	7.2	71	322	-7.02	364 543	0.14	69	397	14.83	450 209	23.67	75
LNID	91 865	304	0.0	279 422	0.0	78	288	-5.34	264 496	-5.34	76	338	11.07	310 348	11.07	81
EID	129 503	390	-0.2	505 264	2.7	81	350	-10.59	452 615	-8.01	78	427	9.11	552 360	12.27	84
Area-Weighted Total	383 246	346	-0.7	1 326 002	5.3	72	318	-8.77	1 217 797	-3.26	70	386	10.73	1 478 184	17.43	75

Actual Expansion Limit		2012's Crop Mix - Ks <90%					Low Water-use Crop Mix - Ks <90%					High Water-use Crop Mix - Ks <90%				
Irrigation District	Total Area	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation
	(ha)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)
WID	0	-	-	-	-	-	239	-25.47	91 914	-25.47	68	285	-11.23	109 466	-11.23	74.78
BRID	0	-	-	-	-	-	287	-17.00	302 155	-17.00	66	343	-0.78	361 211	-0.78	71.58
LNID	0	-	-	-	-	-	155	-48.89	142 810	-48.89	58	182	-40.06	167 472	-40.06	62.98
EID	0	-	-	-	-	-	254	-34.93	320 173	-34.93	72	309	-20.89	389 217	-20.89	77.82
Area-Weighted Total	0	-	-	-	-	-	237	-31.92	857 051	-31.92	62	284	-18.39	1 027 366	-18.39	67.64
Future Expansion Limit		**2012's Crop Mix - Ks <90%**					**Low Water-use Crop Mix - Ks <90%**					**High Water-use Crop Mix - Ks <90%**				
Irrigation District	Total Area	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation
	(ha)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)
WID	42 493	258	-19.60	109 585	-11.14	72	224	-30.10	95 274	-22.74	66	277	-13.61	117 747	-4.52	74
BRID	113 315	288	-16.78	326 273	-10.38	67	255	-26.21	289 308	-20.53	63	341	-1.34	386 789	6.25	72
LNID	91 865	165	-45.88	151 211	-45.88	60	155	-48.89	142 810	-48.89	58	182	-40.06	167 472	-40.06	63
EID	129 503	279	-28.73	360 820	-26.66	75	246	-36.95	319 215	-35.12	71	308	-21.09	399 459	-18.81	78
Area-Weighted Total	377 176	251	-27.85	947 890	-24.70	64	224	-35.56	846 607	-32.74	61	284	-18.44	1 071 467	-14.88	68
Future Expansion Limit with Bruce Lake		**2012's Crop Mix - Ks <90%**					**Low Water-use Crop Mix - Ks <90%**					**High Water-use Crop Mix - Ks <90%**				
Irrigation District	Total Area	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation	Irrigation Demand				Standard Deviation
	(ha)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)	(mm)	% with $2012_{Ks=90\%}$	(dam^3)	% with $2012_{Ks=90\%}$	(mm)
WID	48 563	253	-21.27	122 632	-0.56	72	218	-32.02	105 889	-14.13	66	258	-19.64	125 181	1.51	72
BRID	113 315	288	-16.78	326 273	-10.38	67	255	-26.21	289 308	-20.53	63	341	-1.34	386 789	6.25	72
LNID	91 865	165	-45.88	151 211	-45.88	60	155	-48.89	142 810	-48.89	58	182	-40.06	167 472	-40.06	63
EID	129 503	279	-28.73	360 820	-26.66	75	246	-36.95	319 215	-35.12	71	308	-21.09	399 459	-18.81	78
Area-Weighted Total	383 246	251	-28.02	960 936	-23.66	64	224	-35.78	857 222	-31.90	61	282	-19.18	1 078 901	-14.29	67

Appendix D – Irrigation Districts' Blocks Area-weighted Factors

Table 57: Irrigation Blocks Area-weighted Factors

Irrigation Block	Area-Weighted Factor			
	per District	Actual Expansion	Future Expansion	Expansion with Bruce Lake
310	0.31	0.03	0.04	0.04
311	0.11	0.01	0.01	0.01
312	0.11	0.01	0.01	0.01
313	0.30	0.03	0.03	0.04
314	0.16	0.02	0.02	0.02
Total WID	1.00	0.106	0.113	0.127
330	0.04	0.01	0.01	0.01
331	0.14	0.04	0.04	0.04
332	0.18	0.05	0.05	0.05
333	0.41	0.12	0.12	0.12
334	0.08	0.02	0.02	0.02
335	0.12	0.03	0.03	0.03
338	0.03	0.01	0.01	0.01
339	0.01	0.00	0.00	0.00
Total BRID	1.00	0.291	0.300	0.296
349	0.03	0.01	0.01	0.01
350	0.09	0.03	0.03	0.03
351	0.01	0.00	0.00	0.00
352	0.11	0.04	0.04	0.04
353	0.17	0.06	0.06	0.06
354	0.04	0.01	0.01	0.01
355	0.05	0.02	0.02	0.02
356	0.09	0.03	0.03	0.03
357	0.14	0.05	0.05	0.05
358	0.11	0.04	0.04	0.04
359	0.12	0.04	0.04	0.04
360	0.05	0.02	0.02	0.02
Total EID	1.00	0.348	0.343	0.338
340	0.09	0.02	0.02	0.02
341	0.16	0.04	0.04	0.04
342	0.17	0.04	0.04	0.04
343	0.51	0.13	0.12	0.12
344	0.06	0.02	0.01	0.01
Total LNID	1.00	0.254	0.244	0.240
TOTAL All Districts		**1.00**	**1.00**	**1.00**

Appendix E – Step by Step Method for Generating WRMM Scenarios based on New IDM's Files

1. WRMM Structure (adapted from Alberta Environment 2002)

The Water Resources Management Model (WRMM) comprises two computer programs linked together by shared data files: the Model Simulation Program (WRMM) and the Output Plotting Program (PLOTSIM).

The primary data file used for running the WRMM is the Simulation Control File (SCF) where all the simulation parameters as well as the physical and penalty components of the river system are defined. Details on the content and how to modify the SCF file can be found in the Computer Program Description: Water Resources Management Model (Alberta Environment 2002).

For planning studies involving input data from the Irrigation Management Model (IDM) of Alberta Agriculture and Forestry (AAF), the time-series of historical data are stored in the Hydrometeorologic Base Data File (HBDF) and the Irrigation Base Data File (IBDF).The IBDF is created by the Irrigation Requirements Model (IRM), which computes consumptive demands and return flows for an irrigation district, based on crops, soil types, irrigation equipment and meteorology. The historical water supply and demand data is stored in the HBDF file.

The WRMM reads the SCF, HBDF and IBDF files and generates the Simulation Output Files; the OUTSIM, which comprises the simulated values and the OUTID, which contains the ideal values for each time interval and each component. The simulation results can be further analysed by using the OUTSIM and OUTID data as input into commercially available software such as spreadsheet or database. The PLOTSIM program (Result Viewer.exe) could also be used in order to rapidly scan the Simulation Output Files in graphical format.

2. WRMM Runs Procedure

The WRMM can be run using the following steps:

1. Save all the original WRMM files provided by AEP in a back-up folder to keep an unmodified version of the files
2. Create a new folder using a representative name of the scenario analysed with all the files from the WRMM model: SCF, OutsimOutid MDB database, HBDF, IBDF and the executive program file (wrmm10.8.327.exe)
3. Run the model by double clicking on the executive file

4. After the model is run for the first time, additional files will appear in the folder: Scfecho, OUTSIM, OUTID, debugf, debugdb
5. Note that new scenarios simulation require the use of the Bassano Carseland Check Utility program, which is described below

Figure 77 presents an example of the folders and files used to run the WRMM. In the case presented, the IBDF files are: S9C0M0P9_BRI, S9C0M0P9_EID, S9C0M0P9_LNI and S9C0M0P9_WID.

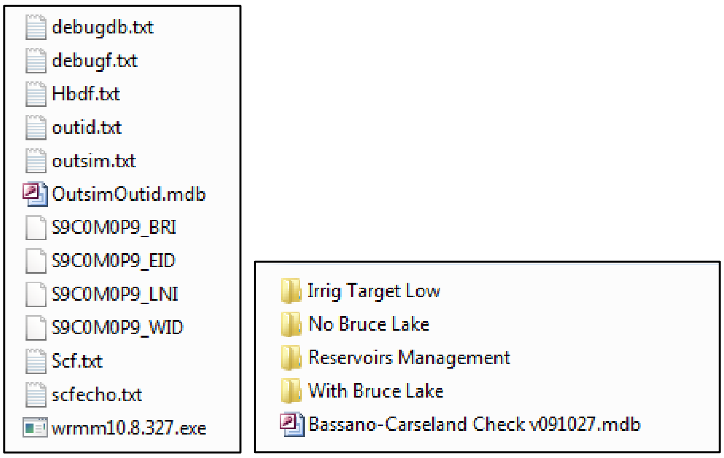

Figure 77: WRMM Scenario Folders and Files

The Bassano Carseland Check utility program is run for each new scenario created as follow:

1. Open the Bassano Carseland Check program and click on enable editing (Bassano-Carseland Check v091027.mdb);
2. Verify that "Bassano" and "One Location Only" check boxes are selected;
3. Click on "Open OutsimOutid.mdb";
4. Select the database in the appropriate folder of the scenario to be adjusted;
5. If the "Required Changes" table appearing in the upper right of the screen is empty, then there is no need to run the utility because no flow changes have to be done;
6. If the cells of the "Required Changes" table are not empty, then the utility is run by clicking on the "Make Adjustment HBDF.txt" option appearing in the lower left corner;
7. After the utility program is run, a new HBDF text file with the adjusted flow data will appear in the same folder as where the Carseland Basano Check program is located;
8. The content of the new HBDF file created by the utility program need to be copied and pasted under the "Bassadj" section of the existing HBDF file located in the folder of the scenario being assessed;
9. The WRMM model is run again after the changes in the HBDF file has been saved ;

10. Finally the steps 1 to 4 are repeated to make sure the “Required Changes” table is now empty and no more flow data has to be adjusted;
11. If the “Required Changes” table still shows some data that needed to be adjusted than the steps 6 to 10 are repeated;
12. In case the “Required Changes” table is still not empty at the third iteration, click on the “Make Zero Output.txt” button to generate a HBDF text file containing a sequence of flow all equal to zero;
13. The steps 8 to 10 are repeated using the new flow sequence equal to zero.

Figure 78 presents the Carseland Bassano Check Utility program steps.

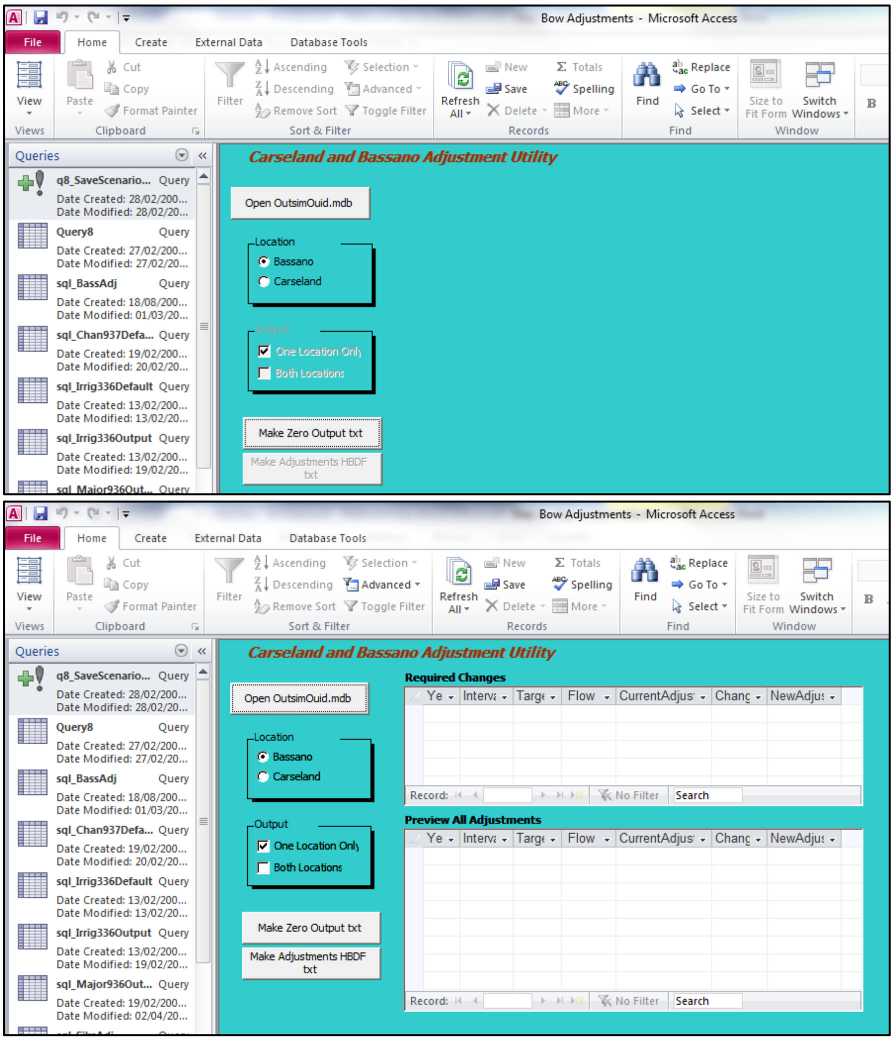

Figure 78: Carseland Bassano Check Utility Program Steps to Adjust the Bow River Minimum Flow to Maintained Downstream of Bassano

3. Creating WRMM Scenarios Using IDM Files Procedure

The IDM model output comprises IBDF files (".ibd"), HBDF files (".hbd") and sometimes mm files (".mm") for each irrigation districts as well as other mm files for the First Nations irrigation demands. The IBDF file of a given irrigation district corresponds to the time-series of the weekly consumptive use and return flow data for each irrigation blocks of this district. The values are given in cubic meter per second. The HBDF file of a given irrigation district corresponds to the time-series of the weekly inflow data for each irrigation blocks of this district. The values are also given in cubic meter per second and are normally equal to zero except for some blocks at the week 41.This inflows represent the drainage of the canals at the end of the season. The mm file corresponds to the time-series of the weekly consumptive use for some irrigation blocks of some of the irrigation districts. The values are given in millimeters.

The irrigation demand data for the WRMM can be changed using the following steps:

1. Copy and paste all the content from the HBDF and mm files of the IDM inside the HBDF file of the WRMM at the appropriate space; look for specific irrigation block name (ex: Irrig338) in the HBDF file and replace its consumptive use or inflow data by the new ones (Figure 79);
2. Copy and paste all the content from the IBDF files of the IDM inside the appropriate IBDF file of the WRMM; each irrigation district usually has individual IBDF file containing all their irrigation blocks consumptive use and return flow sequences;
3. Make sure that the IBDF file name indicated for every irrigation block demand in the "$WATDEM" section of the SCF file is the same as the IBDF file name identifying the irrigation district at which the block is pertaining (Figure 80);
4. For scenarios involving irrigation blocks expansion, the new irrigation block area has to be updated in the SCF as well in the section "$PHYSYS" for each block concerned (Figure 81);
5. For scenarios involving change in irrigation demand of the BRID and/or the First Nations irrigation block 336, the "BRIDMIN" component of the HBDF file needs to be updated by the following weekly flowrate sequence in cubic meter per second: 8.5 + Block 336 consumptive use + Block 338 consumptive use.

```
Hbdf.txt - Notepad
File  Edit  Format  View  Help
IRRIG338 1928  86 MM     3806.794
CONSUMPTIVE  USE  AT BLOCK  338
CREATED BY NMM (VERSION 1.7.2) AT 2014/12/10 22:12:55 BY \\VDID-IDM-1\BOB.RIEWE
NETWORK VERSION = "BRID 2012 Model CMhigh exp" (ID=3437 ON AGAPPS10)
YEAR      wk01     wk02     wk03     wk04     wk05     wk06     wk07     wk08     wk09     wk10     wk11     wk12
1928      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1929      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1930      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1931      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000

S9C0M0P9_BRID.mm - Notepad
File  Edit  Format  View  Help
 IRRIG338 1928  85 MM     3534.880
CONSUMPTIVE USE AT BLOCK 338
CREATED BY NMM (VERSION 1.7.2) AT 2013/04/22 11:56:44 BY \\VDID-IDM-1\BOB.RIEWE
NETWORK VERSION = "BRID 2012 Model" (ID=3187 ON AGAPPS10)
YEAR      wk01     wk02     wk03     wk04     wk05     wk06     wk07     wk08     wk09     wk10     wk11     wk12
1928      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1929      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1930      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1931      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1932      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1933      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1934      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
```

Figure 79: Irrigation Block's Consumptive Use Data in the HBDF File of the WRMM from the IDM's "mm" File

```
Scf.txt - Notepad
File  Edit  Format  View  Help
  312
IRRIGAT      313  IR  WID4              RT  WID4      1         S9C0M0P9_WID
  313
IRRIGAT      314  IR  WID5              RT  WID5      1         S9C0M0P9_WID
  314
IRRIGAT      330  IR  BRD1              RT  BRD1      1         S9C0M0P9_BRI
  330
IRRIGAT      331  IR  BRD2              RT  BRD2      1         S9C0M0P9_BRI
  331
IRRIGAT      332  IR  BRD3              RT  BRD3      1         S9C0M0P9_BRI

S9C0M0P9_BRI - Notepad
File  Edit  Format  View  Help
*BLOK330 1928  86 CMS    4330.906        330
CONSUMPTIVE USE AT BLOCK 330
CREATED BY NMM (VERSION 1.7.2) AT 2014/12/10 22:12:05 BY \\VDID-IDM-1\BOB.RIEWE
NETWORK VERSION = "BRID 2012 Model CMhigh exp" (ID=3437 ON AGAPPS10)
YEAR      wk01     wk02     wk03     wk04     wk05     wk06     wk07     wk08     wk09     wk10     wk11     wk12
1928      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1929      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1930      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1931      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1932      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1933      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
```

Figure 80: IBDF File Name Indicated in the SCF File for Defining the Irrigation Block's Ideal Demands

```
IRRIGAT      300  SEN IRR,ELBOW TO BONNYB    0                145.480        1.
IRRIGAT      307  SNR/HIGH                   0                170.540        1.
IRRIGAT      308  SNR/CARSE                  0                473.055        1.
IRRIGAT      309  SNR/BASS                   0               1232.210        1.
IRRIGAT      319  JUN IRR,ELBOW TO BONNYB    0                   .400        1.
IRRIGAT      377  JNR/HIGH                   0                410.050        1.
IRRIGAT      378  JNR/BASS                   0                342.190        1.
IRRIGAT      695  DS TRAVS                   0                412.227        1.
IRRIGAT      765  SEN IRR,BPAW TO CALGARY    0                168.948        1.
IRRIGAT      768  SEN IRR,BONNYB TO HIWD     0                114.360        1.
IRRIGAT      769  JUN IRR,BONNYB TO HIWD     0                192.351        1.
IRRIGAT      310  WID                        1              13218.895        1.
  510      3  1.0
IRRIGAT      311  WID                        1               4725.699        1.
  511      3  1.0
IRRIGAT      312  WID                        1               4860.740        1.
  512     25  1.0
IRRIGAT      313  WID                        1              12777.613        1.
  513     23  1.0
IRRIGAT      314  WID                        1               6909.969        1.
```

Figure 81: Irrigation Block's Area in the SCF file

Appendix F – Dry to Wet Years Classification

Table 58 : Ranked Seasonal Streamflow Volume and Area-Weighted Irrigation Demands for Selecting Three Typical Dry, Normal and Wet Years

Year	Seasonnal Streamflow April – October (dam^3)	Streamflow Rank	Area-Weighted Irrigation Demand (mm)	Irrigation Demand Rank	Total Rank	Rank-Ordered Year	Total
1928	3 273 709	70	306	57	127	**2001**	**2**
1929	2 150 587	39	483	2	41	**1949**	**12**
1930	2 364 565	53	411	14	67	2000	15
1931	1 818 815	19	432	11	30	**1936**	**18**
1932	2 775 920	66	310	55	121	1937	20
1933	2 525 576	58	435	10	68	1984	23
1934	2 207 771	44	407	16	60	1979	24
1935	2 268 907	50	412	13	63	1931	30
1936	1 710 508	14	470	4	18	1944	30
1937	1 674 406	11	435	9	20	1988	30
1938	2 418 587	55	351	35	90	1977	33
1939	1 916 054	27	363	29	56	1985	33
1940	1 838 579	22	391	21	43	1960	34
1941	1 426 697	3	329	44	47	1957	36
1942	2 228 852	48	236	65	113	1943	40
1943	2 061 780	35	470	5	40	1929	41
1944	1 644 365	8	378	22	30	1940	43
1945	1 905 513	25	356	33	58	1994	43
1946	2 203 027	42	328	45	87	1941	47
1947	2 525 312	57	306	58	115	1961	52
1948	2 809 387	67	335	41	108	1989	53
1949	1 506 807	5	439	7	12	1939	56
1954	3 024 156	69	310	54	123	1983	56
1955	2 056 510	34	361	30	64	1945	58
1956	2 217 784	46	310	56	102	1970	59
1957	1 829 356	21	410	15	36	1987	59
1958	2 114 748	38	353	34	72	1996	59
1959	1 983 779	31	335	42	73	1934	60
1960	1 905 777	26	436	8	34	1971	61
1961	2 263 900	49	480	3	52	1973	61
1962	2 039 381	33	357	32	65	1935	63
1963	2 224 109	47	316	48	95	1955	64
1964	2 204 608	43	350	36	79	**1962**	**65**
1965	2 730 331	65	208	67	132	1997	65
1966	2 474 453	56	208	68	124	1930	67
1967	2 680 525	63	404	18	81	1933	68
1968	1 964 015	30	294	59	89	1982	69
1969	2 568 266	59	343	40	99	1958	72
1970	1 820 396	20	346	39	59	**1959**	**73**
1971	2 098 146	37	377	24	61	1975	75
1972	2 701 344	64	318	47	111	**1964**	**79**
1973	2 072 848	36	371	25	61	1967	81
1974	2 573 273	60	377	23	83	1980	81
1975	1 674 933	12	261	63	75	1974	83
1976	2 396 451	54	311	53	107	1998	83
1977	1 405 089	2	358	31	33	1992	86

1978	1 881 533	24	228	66	90	1946	87
1979	1 477 557	4	398	20	24	1968	89
1980	1 941 088	29	312	52	81	1938	90
1981	2 859 719	68	287	61	129	1978	90
1982	1 850 701	23	322	46	69	1990	90
1983	1 684 947	13	330	43	56	1963	95
1984	1 528 680	6	406	17	23	1969	99
1985	1 592 188	7	369	26	33	1986	101
1986	2 273 387	51	313	50	101	1956	102
1987	1 663 075	10	315	49	59	1976	107
1988	1 789 564	18	419	12	30	1948	108
1989	1 751 354	15	347	38	53	1999	109
1990	2 669 985	62	364	28	90	1972	111
1991	2 575 381	61	289	60	121	1993	111
1992	1 775 861	17	198	69	86	1942	113
1993	2 181 682	41	180	70	111	1995	114
1994	1 764 793	16	364	27	43	1947	115
1995	2 355 078	52	283	62	114	1932	121
1996	2 157 702	40	398	19	59	1991	121
1997	1 937 663	28	350	37	65	**1954**	**123**
1998	2 026 732	32	312	51	83	1966	124
1999	2 210 933	45	257	64	109	1928	127
2000	1 651 216	9	451	6	15	**1981**	**129**
2001	1 376 628	1	526	1	2	**1965**	**132**
Mean	2 103 676		351				71
Upper Quartile	2 362 193		403				98
Lower Quartile	1 796 877		311				44
Standard Deviation	416 912		71				33