INTEGRATED WATER RESOURCES MANAGEMENT MODELLING FOR THE OLDMAN RIVER BASIN USING SYSTEM DYNAMICS APPROACH

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ABSTRACT

Limited freshwater supply is the most important challenge in water resources management, particularly in arid and semi-arid basins. However, other variations in a basin, including climate change, population growth, and economic development intensify this threat to water security. The Oldman River Basin (OMRB), located in southern Alberta, Canada, is a semi-arid basin and encompasses several water challenges, including uncertain water supply as well as increasing, uncertain water demands (consumptive irrigation, municipal, and industrial demands, and non-consumptive hydropower generation, and environmental demands). Reservoirs, of which the Oldman River Reservoir is the largest in the basin, are responsible for meeting most of demands, and, protecting the basin's economy. The OMRB has also faced extreme natural events, floods and droughts, in the past, which reservoir management plays a critical role to adapt to. The complexity of the climate, hydrology, and water resource system and water governance escalates the challenges in the basin. These factors are highly interconnected and establish dynamic, non-linear behavior, which requires an integrated, feedback-based tool to investigate. Integrated water resources (IWRM) modelling using system dynamics (SD) is such an approach to tackle the different water challenges and understand their non-linear, dynamic pattern. In this research study the Sustainability-oriented Water Allocation, Management, and Planning ($SWAMP_{OM}$) model for the Oldman River Basin is developed. $SWAMP_{OM}$ comprises a water allocation model, dynamic irrigation demand, instream flow needs (IFN), and economic evaluation sub-models. The water allocation model allocates water to all the above-mentioned demands at a weekly time step from 1928 to 2001, and under different water availability scenarios. Meeting irrigation demands relies on the crop water requirement (CWR), which is calculated under different climatic conditions by

the dynamic irrigation demand sub-model. This sub-model estimates the weekly irrigation demand for main crops planted in the basin. $SWAMP_{OM}$ also computes environmental demands or instream flow need (IFN) for the Oldman River, and allocates water to rivers to meet IFN under different policy scenarios and uncertain water supply. Finally, the major water-related economic benefit in the basin, earned by agriculture and hydropower generation, is computed by the economic evaluation sub-model. The results show that $SWAMP_{OM}$ could reasonably satisfy the demands at a weekly time step and provide an adequate estimation of the crop water requirement under different hydrometeorological conditions. Based on the $SWAMP_{OM}$'s results, the average annual irrigation demand is 306 mm over the historical time period from 1928 to 2001 in the main irrigation districts. The average weekly instream flow need of the Oldman River is calculated to be approximately 20.5 m^3/s, which can be met in more than 97% of weeks in the historical time period. Average annual water-related economic benefit was computed to be 192.5 M$ in the OMRB. It decreased to 82.8 M$ in very dry years, and increased up to 328.6 M$ in very wet years.

This research also developed different sets of Oldman Reservoir's operation zones, resulting in trade-offs between the optimal economic benefit, water allocated to the ecosystem, minimum floodwater and minimum flood frequency. This helps decision makers to decide how much water should be stored in the reservoir to meet a specific objective while not sacrificing others. A multi-objective performance assessment, Pareto curve approach, is applied to identify the optimal trade-offs between the four objective functions (OFs), and 18 different optimal, or close to optimal sets of operating zones are provided. The decision regarding the operating zones depends on decision makers' preference for higher economic benefit, water allocated to IFN, or flood security. However, the set of operating zones with minimum floodwater causes 11 less flood events; the operating zones with maximum economic benefits result in 4.1% more financial gain;

and the zones with maximum water allocated to IFN lead to 10.1% more ecosystem protection in the whole 74 years, compared to current zones.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1. 1. Background

Water is an essential source of life. The earliest human civilizations arose near rivers where fresh surface water was abundant. Later, advances in technology and human capability of building water structures helped to transport water and provided more water accessibility. However, the availability of clean and fresh water has been limited (Hinrichsen and Tacio, 2011). Nowadays, approximately 1.7 billion people live in areas where water availability, climate change, population growth and economic development are provoking water resources problems (IPCC, 2007). Arid and semi-arid basins, in particular, face more threats to water security. Besides water shortage in such basins, specific climatic and hydrological conditions, complex water governance and complex water systems may increase the challenges in water management. These challenges are extremely interconnected, and a dynamic, closed-loop behavior is dominant on their interaction, so that a past behavior of a water component affects its future behavior (Ahmad and Simonovic, 2000), and also the future behavior of the whole water system. To address all these challenges and investigate their dynamic connections in a basin, an integrated, feedback-based insight is required for water managers.

The Oldman River Basin (OMRB), located in southern Alberta, a sub-basin of the South Saskatchewan River Basin, encompasses almost all the above-mentioned threats to water security faced worldwide. In addition to water supply and water demand uncertainty, the complexity of the basin's water resources system and specific climatic and hydrological conditions exacerbate the challenges of the OMRB's water management. While a water resources management model (WRMM) has been developed for all sub-basins of the South Saskatchewan River Basin (Alberta Environment, 2002), it may not integrally examine all water problems in the basin, and is only designed to allocate water to users. However, in addition to meeting all users' water demands in the basin, it is important to balance human and environmental uses, maintain sustainable aquatic ecosystems and economic uses, and adapt to extreme natural events, like droughts and floods. WRMM also is an optimization-based model, which is not capable of capturing interactions and feedback loops among the variables of the water resource system. There is therefore a need to develop an integrated model for the Oldman River Basin that addresses all water resources threats, and explores their dynamic impacts on the water system. This is the main purpose of this thesis.

A dynamic integrated model also enables the participation of decision makers in solving water challenges in a basin, and facilitates scrutinizing the effect of different water policies on a water system. It helps the decision makers to reach decisions on water allocation to each sector in different water systems facing different water problems under different meteorological and hydrological conditions. In a water resource system, which is highly regulated with infrastructure, like dams, reservoir operation has a critical importance to balance all water security objectives. To meet these objectives, reservoir operating rules should be optimally identified. This is a further objective of this thesis.

1. 2. Statement of Problem

Water availability in terms of quantity and quality has dictated its use, but other factors, including hydrological and ecological conditions, climate variability, socio-political conditions, and policy and governance controls on water management are involved to solve water challenges

(Biswas, 2008). These factors are connected and follow a complex, non-linear behavior. As an example, extreme natural events related to water, including floods and droughts, have affected the economy and society. During drought conditions, tensions between water users, specifically between human uses and environmental flow needs, increase and respecting environmental flow needs will be necessary. Where water resources cross provincial/international borders, balance between upstream and downstream water users is another important issue and socio-political conditions play a crucial role to keep this balance (Wheater and Gober, 2013).

To tackle these water security threats multiple water resources management models have been developed, but more comprehensive, holistic, multidisciplinary tools have been recommended (Norman et al., 2011). The models should not only address all water management challenges, but also present the sensitivity of water resources systems to different climatic and non-climatic "What-if" scenarios (Gober, 2013). Integrated water resources management (IWRM) is such an approach that has been proposed to study human system, environment, and economy all together (Biswas, 1978; Gallego-Ayala, 2013). Mitchell (1990) argued that IWRM should consider ecological systems, interaction between the climate, land, and water, and connections between water and socio-economic development. Therefore, IWRM should investigate all physical, economic, political, social, and legislative aspects of a water system (Molina et al., 2010).

There are two types of views to analyze complex systems like water resources systems, event-oriented or linear causal thinking, and closed-loop or non-linear causal thinking. In linear thinking, the connection between the components of a system is unidirectional to create an outcome, and the outcome has no feedback to the input (Bagheri, 2006). In addition, it is assumed that there is no interaction between future state and current state of the system in linear thinking (Mirchi et al., 2012). However, in complex water resource systems, components are interconnected and feedback loops characterize the system's structure. In fact, closed-loop or non-linear causal thinking controls the behavior of such complex systems. Hence, it is necessary to develop IWRM models in an environment that can reflect the dynamic, loop-based interactions among different components of the water systems. System dynamics (SD) is such approach to scrutinize the behavior of systems in various aspects like management, environmental change, politics, economic behavior, and engineering (Bagheri, 2006). The SD approach can determine how change in one area of a system affects other areas, and also the whole system. Therefore, it is a practical, user-friendly simulation environment for the incorporation of decision makers and stakeholders to examine the effect of their policies on the water system, even in the future with a delay.

IWRM models that cover all water resource system aspects and components, and improve decision making under uncertainty, have not been widely developed in Canada so far (Norman et al., 2011). Thus, there is a need to develop such an all-inclusive IWRM model in a dynamic environment.

In order to implement the IWRM modeling approach, the Oldman River Basin (OMRB) was chosen as a case study in this thesis. The OMRB, as a semi-arid basin, has an average annual precipitation less than 490 mm (AMEC, 2009) and the natural flow of the Oldman River in the headwaters is about 56 m^3/s. The basin has 10 large Irrigation Districts (IDs), which are the largest water consumers. The OMRB encompasses several threats to water security faced worldwide. Uncertain water supply as well as increasing and uncertain water demand in the basin, mostly as a result of global warming, population growth, and agricultural development, are the main sources of water challenges. Furthermore, the complexity of the climate and hydrology, and the complexity of the water resource system and water governance escalate these challenges (These complexities and characteristics of the basin will be thoroughly discussed in chapter 3). The IWRM model should address the following water challenges in the basin (Figure 1-1):

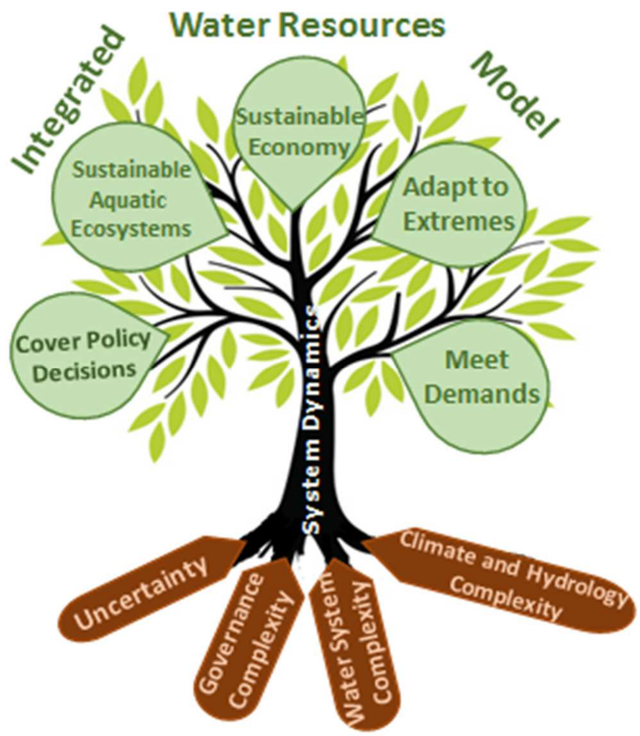

Figure 1.1: Schematic of the scope of the IWRM model

I. The surface water of the basin is fully allocated to different users. The model should meet all current irrigation, industrial, and municipal demands, as consumptive users, and satisfy ecosystem and hydropower generation demands, as non-consumptive users in a weekly time step. Some climate change scenarios show projected decline in the natural flow in the basin up to -18% in future 30 years (AMEC, 2009). Therefore, the model should be able to estimate future water users' demand, and fulfill it. Since the basin has faced floods and droughts in the past, the model should also have the capability to adapt to extreme natural events;

II. Among water users, agriculture has special importance for the economy of the OMRB and Canada. The basin has 10 large Irrigation Districts (IDs) that require careful consideration in the water allocation. The amount of water allocated to IDs is based on crop water requirement (CWR), which is affected by climate change increasing the demands in the OMRB (Pomeroy et al., 2009). The model should estimate the CWR and address the impact of changes in water supply on the water allocated to irrigation districts, crop production efficiency, and finally on the basin's economy under different what-if scenarios of water availability.

III. Flow regulation and off-stream water diversion change the flow regime, and endanger sustainable aquatic ecosystems in the basin. It is recommended that river flows should not be less than a specific amount of water in each week. This amount of water is defined as instream flow need (IFN). The model should be capable of calculating IFN, and allocating enough water to rivers to meet IFN under current hydrological conditions. There are different methods to compute IFN, like the fish rule curve (FRC) and the Alberta desktop method (ADM). In common approaches of estimating IFN in Alberta, a percent of natural flow is allocated to ecosystem and maintained in the rivers. This percentage value is called the "IFN percent of natural flow component". It is different for each section of the Oldman River, but it is 75% on average. Satisfying IFN under different policy scenarios of uncertain water supply is within the scope of this thesis. Furthermore, this percentage value for each section of the Oldman River will be changed and IFNs will be calculated. Afterwards, the impact of this change on the water allocated to IFN, and also on the basin's economy will be investigated under different scenarios of water supply availability.

IV. Water resources in the basin are highly regulated. There are four important dams, which are responsible for meeting the demands of the majority of users in the basin and support sustainable economic development and aquatic environment. Among them, the Oldman River Reservoir, which is the largest reservoir in the basin, has also the task of providing the water requirement of the Saskatchewan apportionment channel. The minimum water demand of this channel is 42.5 m^3/s which is met by the Bow and Reddeer Rivers, besides the Oldman River. Hence, not only does the Oldman reservoir's operation play a crucial role in managing the water in the basin, but it is also important to secure flows to the downstream province of Saskatchewan. This role becomes critical under specific hydrometeorological conditions, like drought or floods, to keep balance between the basin's economy and ecosystem while preventing floods and decreasing drought effects. Therefore, reservoir operating zones should be most-optimally identified. This research also aims to provide decision makers with guidelines, including different sets of operation zones resulting in trade-offs between the optimal economic benefit, water allocated to the ecosystem, and flood protection. Using these guidelines, decision makers can easily decide how much water should be stored in the reservoir to meet a specific objective while not sacrificing others.

1. 3. Research Purpose

The purpose of this research is to improve decision making under uncertain water supply and demand by developing an integrated water resources management model for the Oldman River Basin. The specific objectives are to:

I. Develop an integrated water resources management model, including water allocation model, dynamic irrigation demand, economic evaluation, and instream flow needs (IFNs) sub-models;

II. Investigate the impacts of changing water availability and IFN's policy on the basin's economy and water allocated to IFNs; and

III. Analyze alternative sets of operating zones for the Oldman River Reservoir using multi-objective performance assessment, the Pareto approach, to identify the most-optimal economic benefits and water allocation to IFN, while avoiding flooding.

CHAPTER 2

LITERATURE REVIEW

This literature review is mostly focused on integrated water resources management (IWRM) modelling. First of all, IWRM models and some approaches applied to develop them will be described. Then, uncertainty in water supply and demand will be discussed. The last part of this chapter will assess the Pareto approach as a solution to balance economic development, environmental protection, and flood security objectives.

2. 1. Integrated Water Resources Management Modeling

While there are several definitions of IWRM, Biswas (2009) argued that the most comprehensive is the Global Water Partnership's definition. The Global Water Partnership (2000) defined IWRM as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". Considering this definition, IWRM requires a model which not only covers the physical processes (Motando, 2002), but also can represent system feedbacks, and interaction between the physical processes and socio-economic issues. Nikolic et al (2012) also discussed that an IWRM model should have suitable spatial and temporal scales and engage stakeholders in decision making.

So far various integrated water resources management models have been developed across the globe. Molina et al. (2010) proposed an integrated water management model using Object-

Oriented Bayesian Networks (OOBNs) for the Altiplano region of Murcia in Southern Spain. They built a Decision Support System (DSS) to engage stakeholders and assess the effects of a range of management strategies on a complex water system supplied by groundwater from four aquifers. Graveline et al. (2014) also developed an integrated model, which linked physical processes to regulatory and economic issues in Gallego catchment, Spain, to evaluate the effects of water scarcity under global changes on the future state of water. As Harou et al. (2009) argued, such integrated models, which capture hydrologic, engineering, environmental, and economic aspects of water resource systems on a regional scale within a coherent framework are called hydro-economic models. Integrated hydro-economic models represent the interactions between water and the economy, and the impact of economic water use on water availability and quality in the short and long term (Brouwer and Hofkes, 2008). In some research, these models have been extended, and other aspects of water management problems have been added to them. For instance, Cia et al. (2003) developed an integrated hydrologic-agronomic-economic model to manage the water in the Syr Darya River basin in Central Asia. Their model had more characteristics of an IWRM model and included flow and pollutant transport and balance in the basin, irrigation and drainage processes, economic evaluation of pollution control and water conservation, infrastructure improvement with consideration of investment, and institutional rules and policies that govern water allocation. Guan and Hubacek (2008) developed a hydro-economic accounting framework for the North of China to evaluate the linkages between the economy and the hydro-ecosystem. They measured the amount of return flows of different qualities to the respective hydro-sectors, quantified the amount of freshwater that had been contaminated in the regional hydro-ecosystem, examined the impacts of wastewater on the regional hydro-ecosystem, and tracked the sources of water inputs to every economic sector. On a smaller scale, California as an arid state in the USA needed a holistic hydro-economic-engineering model to address the water challenges (Draper et al. 2003). Hence, a model was developed by Draper et al. (2003) to operate surface and groundwater resources and allocate water over the historical hydrologic record considering the economic values of agricultural and urban water use, within physical, environmental, and selected policy constraints. They used an optimization approach to develop their hydro-economic model. Varela-Ortega et al. (2011) also used a combination of optimization and hydrologic models (WEAP) in an arid basin in Spain to examine the spatial and temporal impacts of water and agricultural policies under different climate scenarios. They aimed to recover groundwater resources and conserve rural livelihoods in the basin. In Canada, Ferreyra et al. (2008) applied an IWRM framework to analyze agro-environmental policies for secure water quality in the Province of Ontario. A triangulation strategy was followed, including participant observation, document analysis and semi-structured interviews. They argued that agro-environmental programs should be constructed within "expanded arenas" as a task for IWRM and concluded that source water protection in agricultural areas of Ontario needs more flexible ways of connecting to existing social and political policies.

To implement the IWRM approach, both optimization and simulation models were applied. Optimization is typically used to maximize economic efficiency (Alvarez et al, 2004; and Moghadasi et al 2010), and/or minimize the risk in environmental conservation (Fang et al, 2010; Chang et al, 2011). Cia et al. (2002) used quantitative indicators of sustainability to improve the decision-making process with an optimization model applied to the Syr Darya River Basin in central Asia. Their aim was to manage the water in the irrigation-dominated river basins so that crop water requirements and municipal and industrial water demands are met while negative environmental consequences are minimized. Since IWRM needs a broader, multi-faced modeling, a combination of economic and environmental objectives are more useful. As an example, Wang et al (2009) developed a multi-objective optimization model considering economic, social, and environmental objectives to meet eco-environmental water demand for allocating water resources in a river basin over the long term. They also built a forecasting model to predict domestic and industrial water demands.

Optimization models might be helpful to identify the decision-variable values, which produce the best plan. But, they are based on the assumptions incorporated in the model. Often these assumptions are limiting. In these cases the solutions resulting from optimization models should be examined in more detail, maybe through simulation models, to improve the values of the decision-variables (Loucks and Van Beek, 2005). Simulation models can address “what-if” scenarios to evaluate alternative design and/or operating policies (Loucks and Van Beek, 2005). For instance, George et al. (2011) linked a simulation-based allocation model with a social cost-benefit economic model to analyze different policy scenarios for water allocation and surface and groundwater resource availability in the Krishna Basin, India. Another important characteristic of simulation models to manage water resources is that they allow investigation of the effect of future changes in the water resources systems (Heinz et al., 2007). Therefore, many studies have preferred simulation models to examine the water system behavior under different policies and scenarios (Marques et al., 2006; Kalbus et al, 2011). Another research by Molina et al. (2011) is one example of applying simulation models in integrated water resources management. They simulated an integration of hydrological, economic and social factors using a Groundwater Flow Model (GFM) and a Decision Support System (DSS) based on an object-oriented Bayesian Networks approach for a region in Murcia in Spain. They selected some management strategies to evaluate the possible impacts caused by future water management actions on the water system. In a study by Gober et al (2010), a simulation, hierarchical model (WaterSim) has been developed to examine the effect of different climate conditions and policy choices on water supply and demand conditions in Phoenix, USA. Their model allows for the participation of policy makers and residents in decision processes considering the uncertainties of climate change. Simulation results show significant threats to Phoenix's water security due to global warming and population growth (Gober et al., 2010).

So far various simulation IWRM models have been developed worldwide, allowing model developers and policy makers to investigate alternative “science- and policy-based” scenarios. Nonetheless, there is a strong need to explore simulation models that not only represent complex dynamic water resource systems in a realistic way, but also allow the involvement of end users in model development (Ahmad and Simonovic, 2000; Loucks and Van Beek, 2005; Cai et al. 2012; Beddington, 2013).

As mentioned earlier in chapter 1, system dynamics (SD) is a simulation environment that is valuable for representing complex systems in a way that can facilitate the engagement of stakeholders in the decision-making process. For example, SD was used to propose a water allocation agreement among five states of the Mexican Republic and the national water authorities (Hinojosa-Huerta et al., 2001). SD also is quite suitable for multidisciplinary and multi-actor problems in integrated water resources management (Winz et al, 2009). Davies and Simonovic (2011) examined five water resources experiments to show several benefits of a feedback-based modeling approach. Their experiments included “wastewater treatment”, “reuse programs”, “irrigation expansion”, “animal product consumption” and “alternative dilution factor values”. Their modelling was focused on the nature and structure of the connections between “water resources” and “socio-economic and environmental change”. The results of the five simulations determined the influences of water stress in water quality and water quantity on the water system in the basin. Gastelum et al. (2010) used an SD approach in the Conchos Basin in Mexico to analyze the effect of different water allocation scenarios on water delivery in the United States and agricultural production within the Basin. To analyze the effectiveness of various supply and demand policies in meeting socio-economic and ecological requirements, Wang et al. (2011) developed a dynamic simulation model of a water system in Yulin City, China. Their results show that the most sustainable strategy for saving the economic and ecological status of the region is demand management instruments and conservation measures. Hassanzadeh et al. (2014) developed a modeling framework for IWRM called $SWAMP_{SK}$ (Sustainability-oriented Water Allocation, Management, and Planning), including an irrigation demand sub-model and a cost-revenue evaluation, using the SD approach for the Saskatchewan portion of the South Saskatchewan River Basin in western Canada. Different evapotranspiration equations were applied to estimate the crop water requirement, and they found that the water resources system is sensitive to the selection of these equations. They also simulated $SWAMP_{SK}$ under multiple what-if scenarios based on irrigation expansion and warming climate and concluded that the agricultural expansion leads to a small decline in hydropower production, and obviously results in an increase in the basin's economic benefit. Besides $SWAMP_{SK}$, there are parallel works for developing $SWAMP_{BOW}$ (SWAMP for the Bow River Basin; Gonda (2015)) and $SWAMP_{OM}$ (SWAMP for the Oldman River Basin) which is the main objective of this thesis.

As Mirchi et al. (2012) concluded, system dynamics, as a systems thinking approach, enables integrated understanding of water resources systems in a reliable qualitative and quantitative bases for policy selection, and strategic decision making, while avoiding unsustainable management strategies. It is a multi-disciplinary, multi-sectoral, and participatory approach that can capture the big picture of the problem using feedback loops (Mirchi, 2013). Hence, it is practical to carry out a conceptual, strategic, sustainable water resources model.

For the Oldman River Basin, which is the case study in this research, an IWRM model which addresses hydrologic, engineering, environmental, and economic aspects of water resources systems, and examines the dynamic behavior of components and the whole system has not developed so far. However, Alberta Environment (2002) has been using an optimization-based Water Resources Management Model (WRMM) for the South Saskatchewan River Basin to allocate water to users based on the physical characteristics of the water resource system, water supply, water demand, and operating policies. But, it has some structural limitations. First, it applies negative flow in some points in the water system. The model uses the cumulative amount of water flow in some parts of the basin (shown with big light blue fletchers in figure 2-1) and the amount of local flow is not given in these parts. Therefore, to calculate the amount of local flow in these points, the cumulative flow should subtract from the flows in the previous points. In some weeks, the calculated local flows have negative values. Second, some inflows are assumed in the model, but there are no such flows in the basin (Blue narrow fletchers in figure 2-1). If some of them are deleted, the model cannot be executed. Third, the WRMM solver can become infeasible, for example when the annual flow volume decreases and/or increases by more than 25% and/or the timing of the peak flow is shifted 4 weeks or more (Nazemi et al., 2013). Another minor inadequacy of WRMM is the imprecise dead storage level assumed for some reservoirs found by Sheer et al. (2013). For instance, the dead storage level in McGregor is assumed so low that irrigators could not pull water at that level.

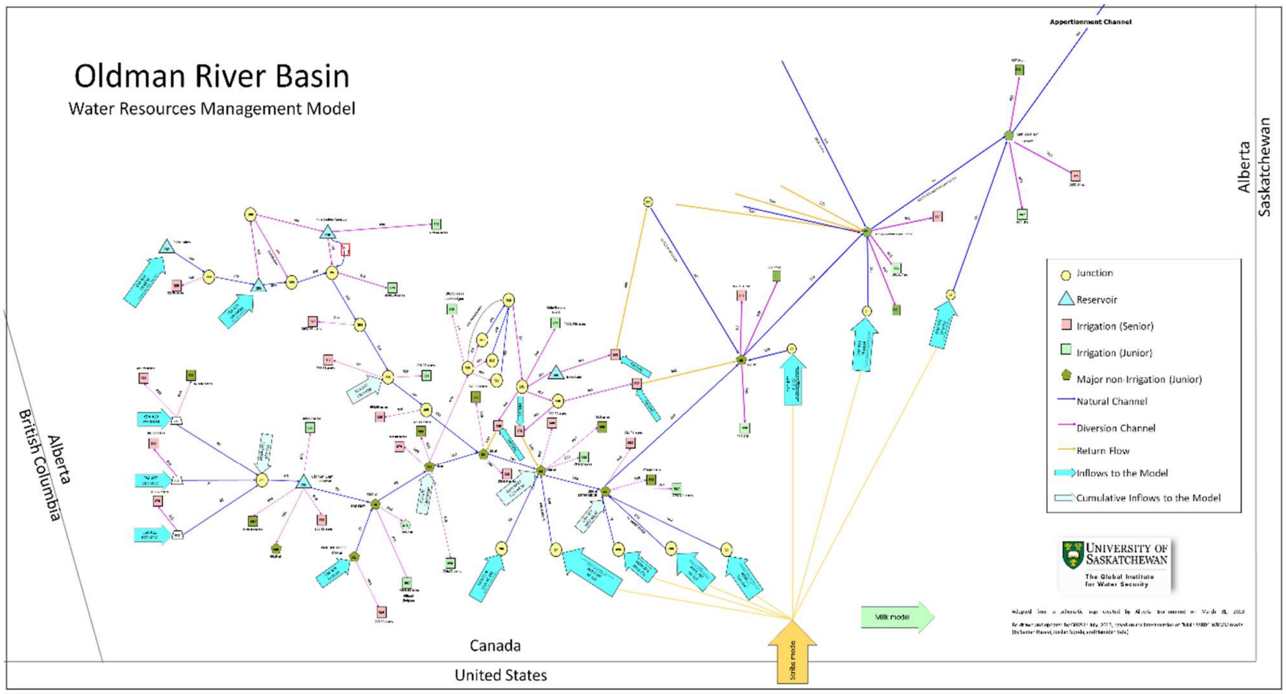

Figure 2.1: Schematic map of the OMRB in the WRMM.

In addition to these minor inadequacies, some more strategic limitations can be tracked in the WRMM. The WRMM does not calculate the irrigation and instream flow demands, under different hydrometeolological condition, and they are fixed data. In fact, a specific amount of water has been assigned for irrigation demand and instream flow needs in the WRMM. It also does not include a sub-model to estimate the economic benefit in the basin. Finally, since WRMM has been implemented using the optimization approach, it is not capable of reflecting the feedback loops among the water system components. It is a black-box for the stakeholders and they cannot track interconnections between the components and investigate how the components affect each other. This capability, along with the estimation of the irrigation and instream flow demands, and also economic benefit, can be well reflected within an SD environment, which is one of this research's purposes. Considering the limitations of the WRMM, there is a need to develop an IWRM model for the OMRB that facilitates "what-if" scenario assessment and captures the connections and feedbacks among the water system variables. This model is implemented within an SD environment.

2. 2. Uncertain Water Supply and Demand

The magnitude and timing of river flows are changing, mainly because of variations in meteorological variables, including precipitation and temperature, and snowpack and glacier melt (Groisman et al., 2001; Milly et al., 2005; Wheater and Gober, 2013). The major reason for these changes is climate variability and climate change. Such variations in river discharge can result in failure to meet the demands (Payne et al. 2004; Archer et al. 2010; Nazemi et al. 2013). Nazemi et al. (2013) demonstrated that changes in the Alberta rivers flow regime mean that Alberta might not be able to meet all demands. Vano et al. (2010) simulated the effects of earlier snowmelt runoff and reduced summer flows on irrigated agriculture. They show that earlier snowmelt leads to increased water delivery limitations and economic losses. On a big scale, Palmer et al. (2010) mapped possible changes in river flows and water stress in basins worldwide. Their projections indicated that nearly one billion people live in areas likely to require proactive or reactive management intervention to mitigate water stress. Otherwise, these changes result in risks to ecosystems and economic losses. Since the Oldman River Basin has experienced such changes in the pattern and characteristics of the river flows (Tanzeeba and Gan, 2012), it is essential to analyze how changes in hydrologic patterns affect meeting the various water demands and the basin's economy.

Another important factor, which affects agricultural productivity and then the basin's economy, is how much water is required by planted crops in the IDs and how much water is available to allocate. Hence, a model should be developed to estimate the irrigation demand. Crop water requirement is the amount of water, which a crop requires for maximum yield. To estimate irrigation demand, different reference evapotranspiration equations (ETo) have been used such as the Penman-Monteith equation (Monteith, 1965), Priestley and Taylor (Priestley and Taylor, 1972), Hargreaves (Hargreaves, 1973), modified Hargreaves (Hargreaves et al., 1985); Hargreaves and Samani (Hargreaves and Samani, 1985); and Maulé (Maulé et al., 2006). Among them, the Penman-Monteith equation calculates the crop water requirement with higher accuracy, but using this equation requires meteorological data that may not be available in all regions (Hassanzadeh et al., 2014). Thus, simple equations have been used in recent studies. Hassanzadeh et al. (2014) compared some simple equations, such as Maulé's and Farmer's equations (Farmer et al. 2011) to estimate the ETo for the South Saskatchewan River (SSR) Basin. They found that the irrigation demand model is sensitive to the selection of the ETo equations. Also, they showed that the results of the Farmer's equation are closer to Penman-Monteith equation's results. Alberta Agriculture, Food and Rural Development (2013) developed an Irrigation Management Model, which uses an ASCE standardized equation, a modified Penman equation, to calculate the reference evapotranspiration. The model estimates the irrigation demands for the most popular crops planted in Alberta. These irrigation demands are an input of Alberta's WRMM. Since $SWAMP_{OM}$ is an emulation of WRMM, the modified Penman equation will be also applied to estimate ETo in this thesis.

2. 3. Balancing Economic and Environmental Protection Objectives While Avoiding Flooding

Water resources management faces both increasing attention to environmental flow requirements and economic growth. This involves complex decision making to allocate water.

Changes in water supply availabilities and water demands can accelerate the competition between human and ecosystem needs. Pahl-Wostl (2007) introduced a conceptual framework to analyze the management regimes of river basins at the global scale that follows a "learning to manage by managing to learn" plan. It was concluded that adaptive water management regimes that consider all characteristics of river basins, specifically environment and economy, are required.

Besides such conceptual frameworks, mathematical models are used to meet economic and environmental protection objectives together. Qureshi et al. (2007) developed an optimization model to analyze the effect of reallocating Murray River Basin water from agriculture to the environment on the economy. The model was simulated under multiple stochastic weather scenarios with and without the possibility of interregional water trade. The results showed a decrease in economic benefit through increasing water allocation to the environment. Cia (2008) also developed an optimization model, which maximized the economic benefit to holistically manage water resources in a basin-scale.

In addition to optimization models with one objective function, there are multicriterion decision methods, which investigate multiple objectives. Lee (2012) used a combination of game theory and multi-objective optimization to balance water quality protection and economic development objectives in the Tseng-Wen reservoir, Taiwan. They aimed to manage land use patterns, therefore, geographic information system (GIS) has been used to spatially organize the geographical data of land use types within the watershed. The Pareto curve approach is another multicriterion decision method that typically follows an optimization method with two or more objective functions (OFs). However, it is practical when the optimization problem involves multiple conflicting objective functions, and there is no single, feasible solution to optimize all objectives together (Augusto et al., 2012). Like other optimization models, one or more parameters are relaxed and optimal objective functions are calculated. In the Pareto curve approach these OFs can be for example, economic benefits and ecosystem targets. Calculated objective functions are plotted in a two dimensional Pareto surface, with the axes showing economic benefit and ecosystem objectives. However, the number of objective functions may increase, and the Pareto curve would change into a higher-dimensional plot. The front of such a plot shows an optimal management plan, which is called the Pareto front. The Pareto approach has several applications in hydrology (to find a set of optimal values for hydrological model's parameters), system management, and hydropower plants (Beven, 2006; Vahidinas and Jadid, 2010; Capon-Garcıa et al., 2011; Vijayalakshmi, 2014). As an example, Ouattara et al. (2012) applied the Pareto approach to study simultaneously ecological and economic issues in hydropower plant utilities management. Genetic algorithms and a decision making tool, called ARIANE^{TM} were used to find Pareto surfaces. They found five Pareto fronts based on the annual hydropower generation cost and five emitted pollutants.

In the last decade, the Pareto approach has been applied in water resources management, and reservoir operation. Suen and Eheart (2006) used the Pareto approach to operate a reservoir in the Dahan River Basin in Taiwan. They aimed to find the optimal trade-off between human water needs and environmental flow regime. Their main goal was to calculate environmental flow needs under different flow magnitude, duration, frequency, and timing conditions. They also defined an objective function, a human needs objective function, to compute the agricultural, and municipal water demands. In another study by Le Ngo et al. (2007), the Pareto curve has been applied to maximize hydropower generation, and minimize flooding in order to reach the optimal control strategies for the Hoa Binh reservoir operation, in Vietnam. Castelletti et al (2013) also focused on the hydropower generation, and flood control in the Hoa Binh reservoir. They projected a novel multi-objective Reinforcement Learning algorithm to compute an approximation of the Pareto front in one single run. Some researches focused on only reservoir flood control operation. Delelegn et al. (2011) used the Pareto approach to minimize the urban flood damage, and Li et al. (2010) used it to optimize the peak flood discharge. They applied a multi-objective shuffled frog leaping algorithm (MOSFLA) to find closer solutions to the Pareto front. On the other hand, Liu et al (2011) found that the Pareto approach is very useful to maximize the hydropower generation in cascade reservoirs. To the best of this author's knowledge, the Pareto approach with multiple objective functions (more than two OFs) has not been applied for reservoir basin management and making a guideline for decision makers to find the best plan based on their priorities on different water management objectives. In most studies, the objective was to find an optimal trade-off between the two objectives, resulting in a two-dimensional Pareto front. In this thesis, the aim is to manage the Oldman River Reservoir in order to overcome the most important water management criticism, and reach the optimal economic benefit and water allocated to the instream flow needs, minimum floodwater and flood frequency through generating a four-dimensional Pareto front.

CHAPTER 3

MATERIALS AND METHODS

As mentioned earlier, this research aims to develop an integrated water resources management model for the Oldman River Basin ($SWAMP_{OM}$), to address the water security challenges under uncertain water supply. This will be achieved through the following steps:

I. Developing a simulation-based water allocation model for the Oldman River Basin (OMRB), through emulation of the existing optimization-based Water Resources Management Model (WRMM);

II. Adding model functionality, in particular, developing dynamic irrigation demand, instream flow need (IFN), and economic evaluation sub-models;

III. Generating a set of feasible scenarios to analyze the impact of water supply uncertainty and change in the IFN percent of the natural flow component, on the basin's economy; and

IV. Analyzing alternative sets of operating zones for the Oldman River Reservoir using multi-objective performance assessment to identify optimal trade-offs between the economic benefits, water allocation to environmental flows and flood control safety objectives.

To develop the $SWAMP_{OM}$, system dynamics (SD), as a modeling approach and object-based simulation environment, is used. SD facilitates engaging different water policies in a modelling process while capturing the dynamic feedback loops dominating the behavior of a complex water resources system (Ford, 1997; Sterman, 2001). This chapter is organized as follows: The chapter begins with an explanation of the Oldman River Basin (Section 3.1), followed by a brief description of WRMM as a source of data on water supply, water demand, operating rules, and allocation priorities (Section 3.2). Section 3.3 explains the SD approach employed to develop the model. Finally, Section 3.4 provides a comprehensive description of $SWAMP_{OM}$ including an explanation of the water allocation model, and economic evaluation, instream flow needs, and dynamic irrigation demand sub-models.

3. 1. Case Study: The Oldman River Basin

The Oldman River Basin, located in southern Alberta (Figure 3-1) is considered semi-arid. The population of the basin is 167,383 people. The basin has a drainage area of approximately 26,700 km^2 (Alberta Environment, 2014) covering three natural regions, including the Rocky Mountains, Foothills, and Grassland (Fiera Biological Consulting Ltd, 2013). The average annual precipitation in the OMRB is 488 mm (AMEC, 2009). In the warm months, April, May, June, July, and August, the amount of precipitation is less than the amount of evapotranspiration; hence, most of the agricultural areas rely on irrigation (AMEC, 2009).

Streamflow in the OMRB is derived mainly from rainfall and snow melt (Byrne et al., 2006). The average annual natural flow of the Oldman River at the headwaters is 56 m^3/s and peak runoff typically occurs in June and early July (OWC, 2011). The headwaters include the Oldman, the Castle, and the Crowsnest, which join together in the Oldman River Reservoir. The St. Mary, Belly and Waterton Rivers are the Southern tributaries and originate from Montana in the United States. They contribute 57% of the flow of the Oldman River. Under an order of the International Joint Commission, the waters of the St. Mary River are shared with the United States so that approximately 30% of the annual streamflow of St. Mary is allocated to the United States (The

State of Saskatchewan River Basin, 2006). The Oldman River and the Bow River join to form the South Saskatchewan River. Climate change scenarios show a range of projected change in the natural flow in the basin from -18% to +4% by 2050 (AMEC, 2009).

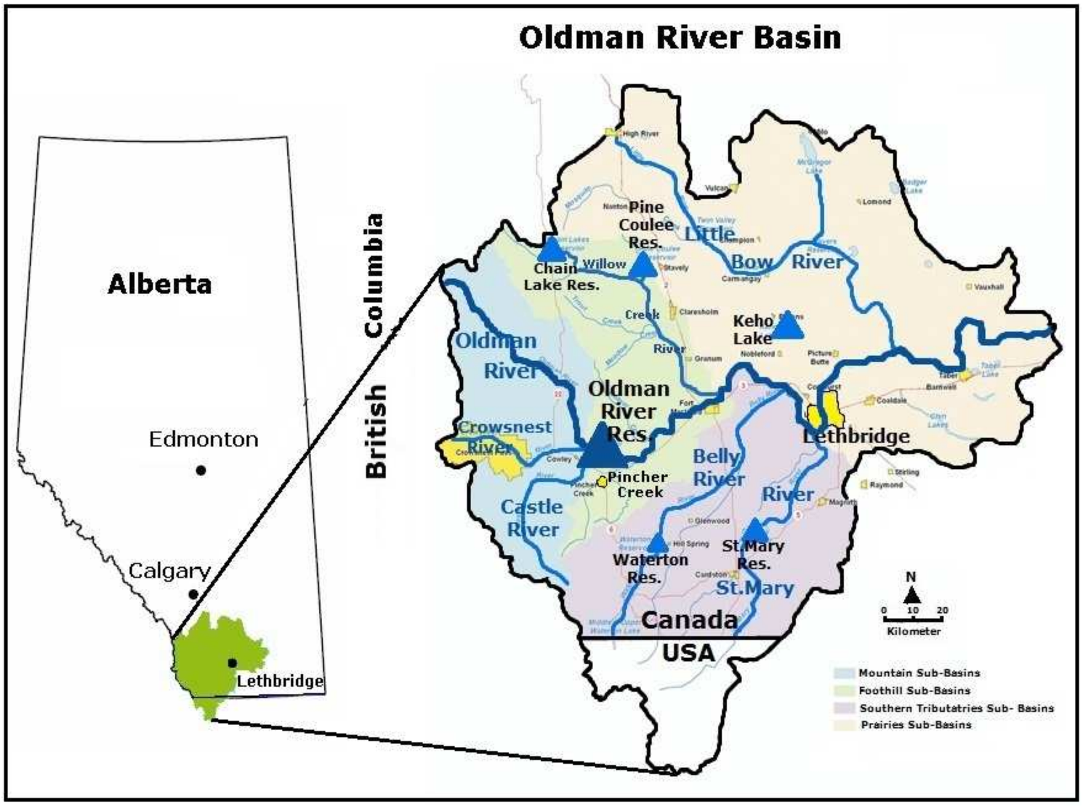

Figure 3.1: The Oldman River Basin (OWC, 2010)

Water consumption in the OMRB mostly relies on the streamflow, and only 2.5% of water requirements are provided by groundwater. The largest water consumer in the basin is agriculture, to which 88% of the total water is allocated (Figure 3-2). Agriculture, as consumptive user, has special importance for the economy of the OMRB and Canada. The main crops grown in the basin are barley, wheat, alfalfa, canola, flax, corn, sugar beet, potato, and beans. Some climate change scenarios show an increase in monthly flow occurring during April and May, and a decrease in August, and September (South Saskatchewan Regional Plan, 2010) in which crop water requirements are high. Such predictions negatively affect the desire of irrigation districts to expand. After agriculture, urban centers (3%), industry (1%) and stock water (1%) are the next largest water consumers in the basin (Figure 3-2). Industrial water is mainly consumed for food and beverage production. Hydropower is also an important non-consumptive water user which has been classified as “other users” in figure 3-2. Hydropower generation is small in the basin and reaches a maximum amount of 32 MWhr in May.

Consumptive water users, such as agriculture, urban centers and industry, reduce the quantity and/or quality of flow, while non-consumptive users like hydropower plant, and instream flow needs, do not cause any overall diminishment in river flow (Adelsman, 1996).

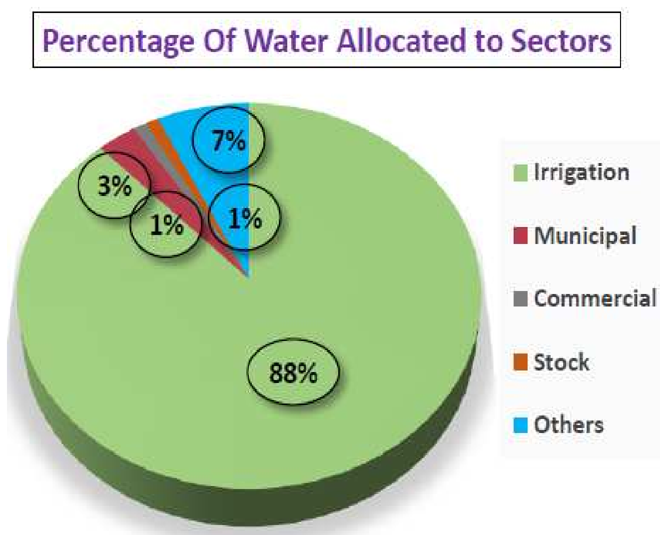

Figure 3.2: The percentage of water allocated to water sectors in the OMRB.

Competition among water users has increased due to urbanization, agricultural expansion, and industrial development. Currently, 100% of the surface flow is allocated to consumptive and non-consumptive users, and it escalates water challenges in the basin. Moreover, degraded water quality and ecosystems are additional challenges for water management in the basin. The basin is a complex human-environmental system with interconnections between terrestrial and aquatic environments, climate, human activities on land, and water management. In general, the growing complexity of the water system and future uncertainty are the main sources of water resources challenges in the basin (Wheater and Gober, 2013):

I. *Climate and Hydrology:* The temperature in the OMRB ranges widely, between -40 and 35 ^{o}C. Large areas of the basin are covered by the Rocky Mountains, thus, characterizing the precipitation amount and phase is difficult. The dominant form of precipitation in the basin is snow. Rainfall, specifically on the snow-covered areas, also plays an important role in the basin's hydrology. Blowing snow, snow sublimation, and snow accumulation are other factors affecting the water balance in the basin (Wheater and Gober, 2013). Flows in the Oldman River greatly change from year to year, with coefficient of variation of up to 55% and flow regulation and water use significantly affect the flow (AMEC, 2009). While climate change scenarios project an increase in precipitation in the OMRB, a decline in the natural flow is expected due to an increase in air temperature leading to a rise in evaporation (Tanzeeba and Gan, 2012) and change in snowmelt contribution to streamflow. The basin experienced extreme natural events in recent decades, including floods (e.g., 2005, 2011, and 2013 floods) and droughts (1999-2004). Warming climate is causing Rocky Mountain glaciers to retreat, hence, the magnitude and timing of river flows are changing (Gober and Wheater, 2013).

II. *Water Resources System:* The water resources system is complex in the OMRB; it includes more than 100 components such as, irrigation districts, hydropower plant, as well as industrial and municipal centers. In addition, there are six important dams, of which the Oldman reservoir is the biggest with full storage capacity of approximately 900 MCM. Water management, flow regulation, flood and erosion control, recreation, and conservation are the main purposes of Oldman reservoir construction (Federal Government, 2003). The reservoir supplies irrigation demands and environmental flow requirements and also meets apportionment requirements for the Saskatchewan province, especially in the dry months. In severe consecutive drought years, the Oldman Reservoir is depleted to the minimum level after one and half years and takes time to recover (South Saskatchewan Regional Plan, 2010).

III. *Water Governance:* Water allocation in the basin is based on the principle of "first in time, first in right" and the use of water (surface water or groundwater) requires a license from the Government of Alberta. However, the federal government has a responsibility to provide the water requirement of First Nation's land (Wheater and Gober, 2013), and first nations have first order to receive water in all water consumption purposes.

In addition, the OMRB -also the Bow River Basin- has inter-provincial commitments to transfer 50% of the natural flows to Saskatchewan via an apportionment channel (Prairie Provinces Water Board, 2011). But, flows have been very close to this limit in consecutive dry years and there are concerns to meet the agreement under drought conditions (Wheater and Gober, 2013).

Although hydrologic characteristics and water management problems in Alberta have been frequently studied, a few studies focused on the Oldman River Basin particularly. As an example, Byrne et al. (2006) addressed current and future water quantity and water quality issues in the OMRB. They discussed that global warming has resulted in a declining trend in alpine and prairie snow pack accumulation affecting streamflow within the OMRB. Their results show that net water supplies are decreasing in the basin, and may possibly lead to a decline in surface water quality;

and finally they emphasized the need for holistic water resources management. Nevertheless, a comprehensive study capturing the water challenges of the basin has not been done. However, the Water Resources Management Model, WRMM, has been developed to allocate the water to all basins in Alberta (Alberta Environment, 2002). The WRMM's data and operating policies have been used to make the IWRM model for the OMRB here ($SWAMP_{OM}$). Thus, it is necessary that a brief description of the WRMM is provided and it will appear in the next section.

3. 2. Water Resources Management Model (WRMM)

WRMM, developed by Alberta Environment, is an optimization-based model that attempts to optimally allocate water to the South Saskatchewan River Basin based on operating rules, and water supply and demand (Alberta Environment, 2010). To allocate the water to the users, WRMM has a schematic map of the OMRB, which is shown in Figure 3.3. On this map, each water component has been named by a number and indicated by a shape. Red fletchers represent minor demands, hexagons signify major demands, squares indicate irrigation fields, triangles represent reservoirs, and circles signify junctions. Historical precipitation, evaporation, and streamflow, as well as weekly demand for each water components are used from 1928 to 2001 at a weekly timestep in the WRMM.

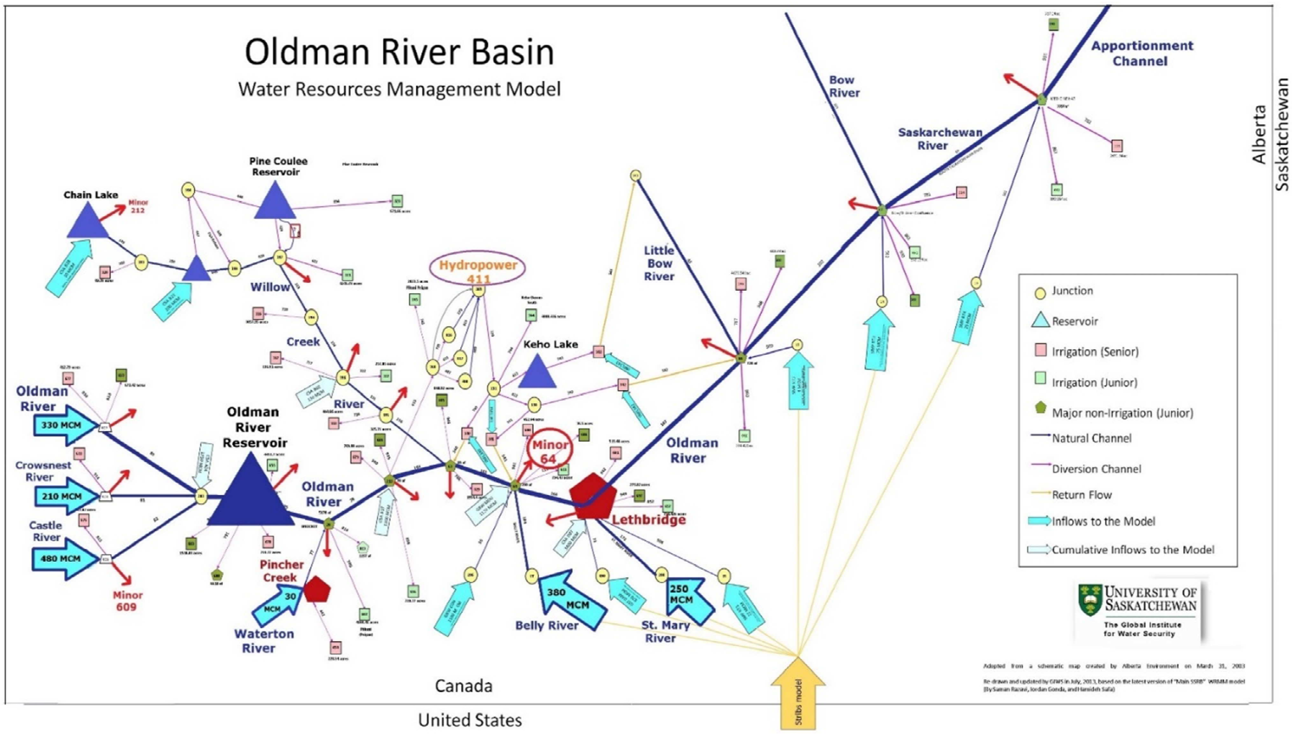

Figure 3.3: Schematic map of the Oldman River Basin (OMRB) as built in WRMM.

Each water component in this schematic map, including irrigation areas, urban centers, hydropower plants and natural channels, has a specific weekly demand and associated penalty zones (Ilich, 2000). Natural channels have flow zones, and municipal and industrial centers have consumptive use zones. Each zone is assigned a penalty (the penalties are notional values and do not have any units) which indicates its priority. Figure 3.4 shows an example of some penalty zones for water components. In figure 3.4 numbers inside the zones are penalties, and represent the priorities for allocating water to each zone, so that the higher penalty represents the higher priority of allocation.

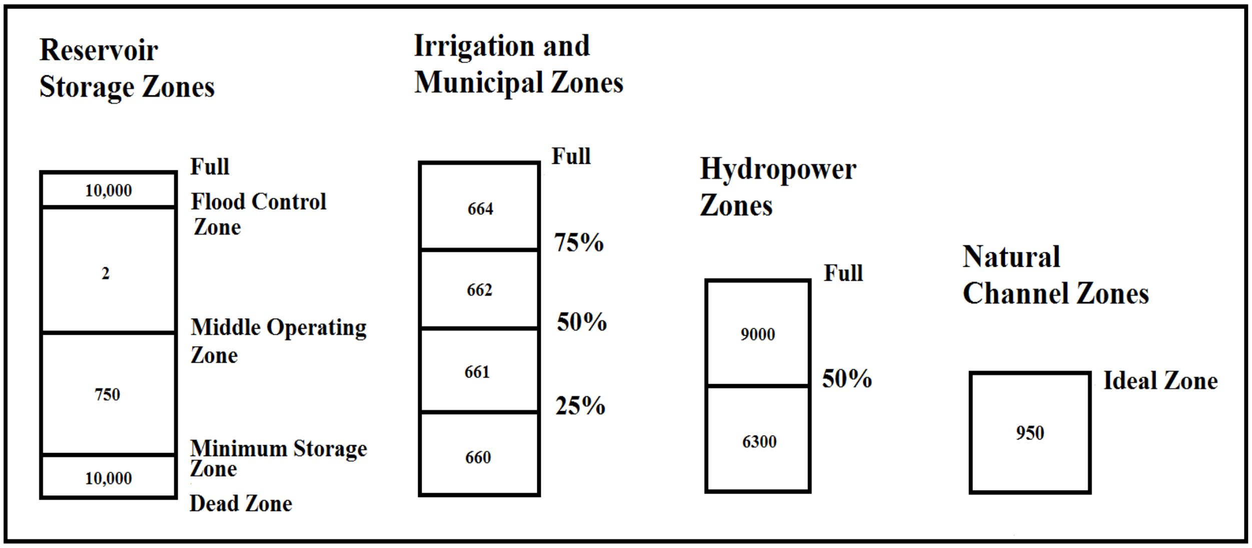

Figure 3.4: Penalty zones for various water components

The urban centers are divided into minor and major units. Minor units have the highest penalty (they are considered as senior water rights holders), and their demand should be met before other users are. However, the major units have a lower penalty in the OMRB. Each major unit has four operating zones whose penalties equal 660, 661, 662, and 664, similar to the penalty of some irrigation fields (figure 3.3, figure 3.4). If all demands are met, no penalty is applied; if 75% of demand is satisfied, the penalty of 660 is used; if 50% and 25% of demand is met, the penalties of 661 and 662 are applied respectively; and if no water is allocated to the user, the penalty would be 664. A hydropower plant, with two penalty zones of 6300 and 9000 receives water second in water allocation order. Some irrigation fields, most of which are private, have penalties of 5000 and 1000 and are the next users to which water is allocated. After these irrigation fields, instream flow need should be met, because of its penalty, which is 950.

Reservoirs typically have two penalty zones representing the physical maximum and minimum storages. If the water stored in the reservoir becomes more than the maximum storage, high numerical value of the penalty (for example 10000 for the Oldman River Reservoir's maximum storage, figure 3.4) is specified. This high numerical penalty is also applied for physical minimum storage, so that if the water stored in the Oldman Reservoir, for instance, becomes less than minimum storage, a penalty of 10000, is specified. Reservoirs may have other penalty zones between the maximum and minimum storage. The Oldman reservoir has two additional penalty zones, including a flood control operating zone and middle operating zone whose penalties are equal to 10,000 and 750, respectively. These additional penalty zones may be higher or lower than the downstream users' penalties. Therefore, depending on these two penalty zones and water users' demand and water users' penalty, the reservoir releases water (Ilich, 1992).

The WRMM utilizes linear programming optimization to minimize water shortage/surplus multiplied by the penalty:

$$Objective = Min \sum (Penalty * |Water\ Allocated - Water\ Demand|) \quad (3.1)$$

WRMM also has some constraints to allocate the water. For instance, the water allocated to irrigation fields, majors, minors and hydropower cannot be more than their demands. The mass balance equation is used to calculate the amount of water stored in reservoirs:

"Storage = Inflow + Precipitation-Evaporation - Water Allocated to Consumers (Minors, Majors, Irrigation Fields) - Water Allocated to Hydropower - Water Allocated to IFN" (3.2)

To clarify how WRMM mathematically works, it is explained by a simple water system (figure 3.5). This system includes a reservoir (blue triangle in figure 3.5) with two penalty zones of maximum and minimum water storages, an urban center (red hexagon), an irrigation field (green square), and one natural channel, all with one penalty zone. The system also has a diversion channel which does not have any penalty. The values of the penalty zones have been indicated inside each water component in figure 3.5. The irrigation field has a demand of 20 m^3/week with a penalty value of 600 (if it is not met); the demand of the urban center is 10 m^3/week with a penalty of 650, and the natural channel's demand is 15 m^3/week and its penalty value is 900. The reservoir is the source to allocate the water to the components. However, the water storage in the reservoir should not be less than minimum or maximum level, otherwise a penalty of 1000 is specified. Therefore, the objective function of this simple system would be:

$$Objective = \min\left(650 * (|10 - x1|) + 600 * (|20 - x2|) + 900 * (|15 - x3|)\right) \quad (3.3)$$

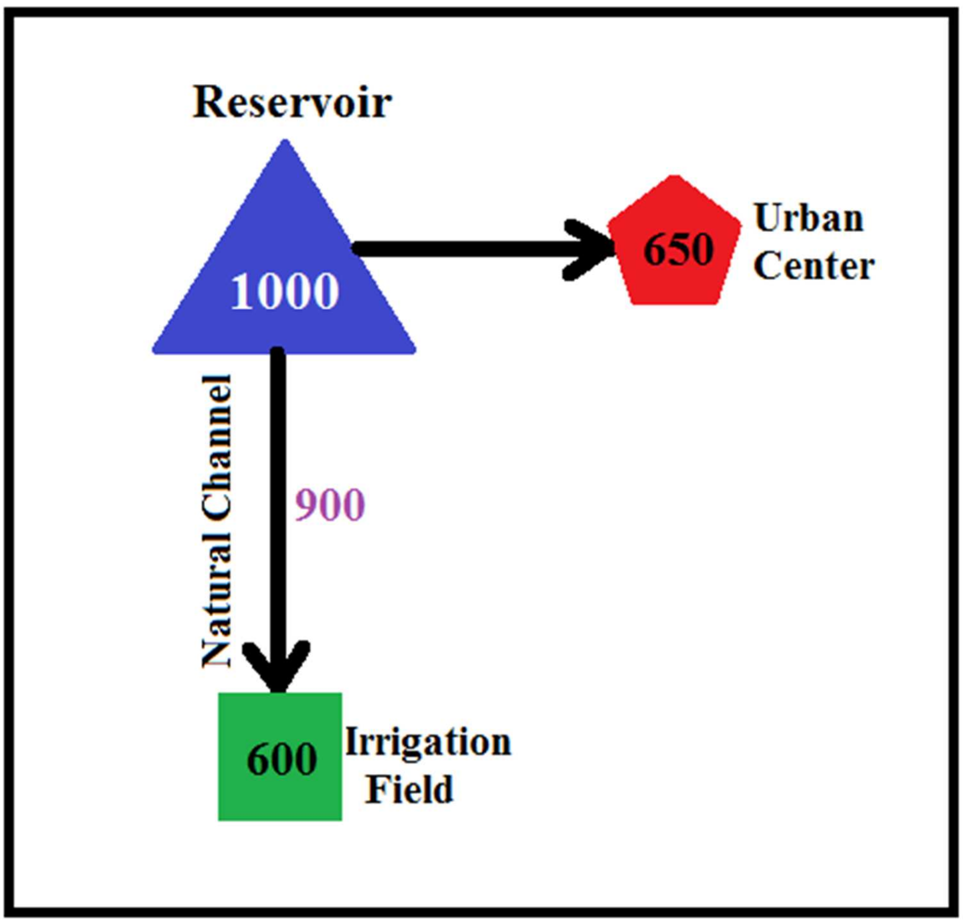

Figure 3.5: Simple water system to explain WRMM operation procedure

where x1, x2, and x3 are water allocated to the urban center, irrigation field, and natural channel, respectively. If the water level in the reservoir goes above the maximum or below the minimum storage, a penalty of 1000 is added to equation 3.3. If WRMM has enough water to allocate to all users, the objective function would be zero. Under water scarcity conditions, it allocates more water to the natural channel to minimize the objective, because its penalty is higher than others. After the natural channel, the urban center, followed by the irrigation field, are set in water allocation order.

3. 3. System Dynamics Approach

System Dynamics (SD) is a simulation environment based on the systems thinking approach being able to combine theory and methods to analyze the dynamic behavior of complex systems (Forrester, 1961; Ford, 1999; Bagheri, 2006). Not only does SD represent processes and related components in isolation, but it also describes the interactions and feedback loops among them over time. It represents a visualization of the connections between the components of a system (Osgood, 2004). SD facilitates understanding of how change in one area of the system results in changes in other areas. Sometimes interaction among the simple components can lead to a complex dynamic pattern in the behavior of the whole system, and the resulting pattern is possibly different than what would be expected through studying each component of the system separately (Osgood, 2004). In fact, the complex behaviors of a system usually originate from the feedbacks among the components, not from the complexity of the components themselves (Sterman, 2000). The socio-economic and environmental systems mostly follow this kind of complex dynamic patterns; therefore, they can be studied using the SD approach.

To understand feedback processes and determine the dynamics of a system, causal loop diagrams (CLDs) are used. A CLD is a powerful graphical tool to visualize the relationships among the components and their interactions with each other (Forrester, 1961; Ford, 1999; Bagheri, 2006).

Each CLD is comprised of arrows indicating causal relationships (Figure 3.6a). The (+) signs at the arrowheads represent that an increase/decrease in variable A causes an increase/decrease in variable B. This would be a positive relationship. On the other hand, a causal link is negative when an increase/decrease in variable A causes a decrease/increase in variable B (Ford, 1999). The dynamics of a system stem from the interaction of two types of feedback loops: positive (reinforcing) loops and negative (or balancing) loops. A positive loop is a source of exponential growth or decline in the system's behavior (Sterman, 2000). As an example, more population causes more babies to be born, (increase in birth rate) and more babies mean more people (increase in population) and so on (Figure 3.6b). However, a negative (or balancing) loop helps the system to self-correct under different conditions (Bagheri, 2006) and tries to make the system stable. This loop generates goal seeking or oscillation behavior in the system. As can be seen in Figure 3.6c, if the water available in the system increases, there would be more water to allocate to users, but if the water allocation goes up, the availability of water in the system declines.

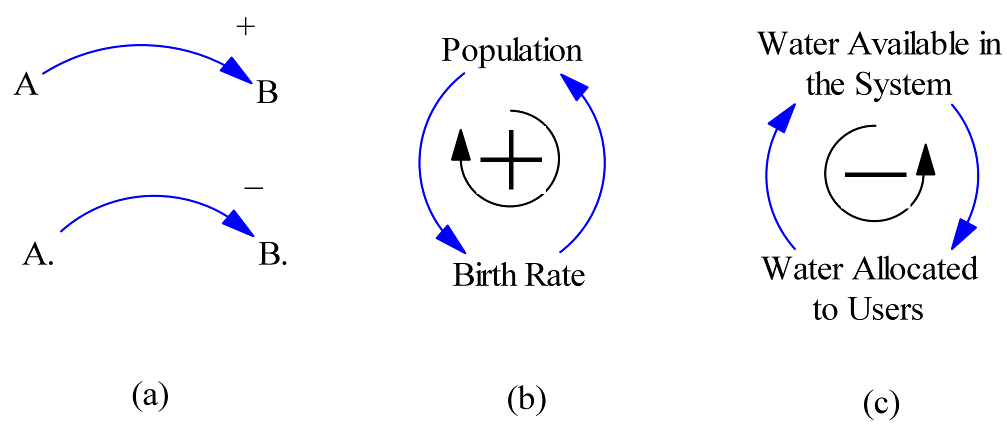

Figure 3.6: Positive and negative causal links (a), and an example of Reinforcing (positive; b) and balancing (negative, c) loops

Feedback loops can be translated to stock-flow diagrams (SFDs) by system dynamics simulation environments such as VENSIM (Systems V, 1996), STELLA (High Performance Systems, 1992) and AnyLogic (XJ Technologies, 2010). These software use stocks, flows, auxiliary variables and connectors to construct a system. Stock variables indicate accumulations and capture the state of the system. All changes to stocks occur via flow variables. Figure 3.7 shows a simple SFD.

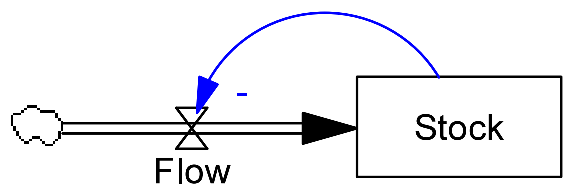

Figure 3.7: Stock-flow Diagram.

Dynamic Behavior of the Water System in the Oldman River Basin: Before developing an IWRM model for the OMRB ($SWAMP_{OM}$), first some feedback loops dominating the behavior of the water system are represented. The water resources system has been divided into two sub-systems to facilitate the description of CLDs:

I. Environmental Sub-system: where climate, terrestrial, and aquatic environments are connected together, and

II. Human Sub-system: where society, economy, and industry are interacting with each other.

Obviously there are interactions between these two sub-systems as well. Based on the two sub-systems in the OMRB, causal loop diagrams (CLDs) were built. Figure 3.8 and figure 3.9 show some dynamic mechanisms existing in the environmental sub-system and the human sub-system, respectively. One typical mechanism in the environmental sub-system originates from the precipitation and evapotranspiration processes. Precipitation creates a reinforcing dynamics and causes increases in water availability in the water resources system, whereas evapotranspiration generates a balancing dynamic and has a negative effect on the water availability in the system (Figure 3.8).

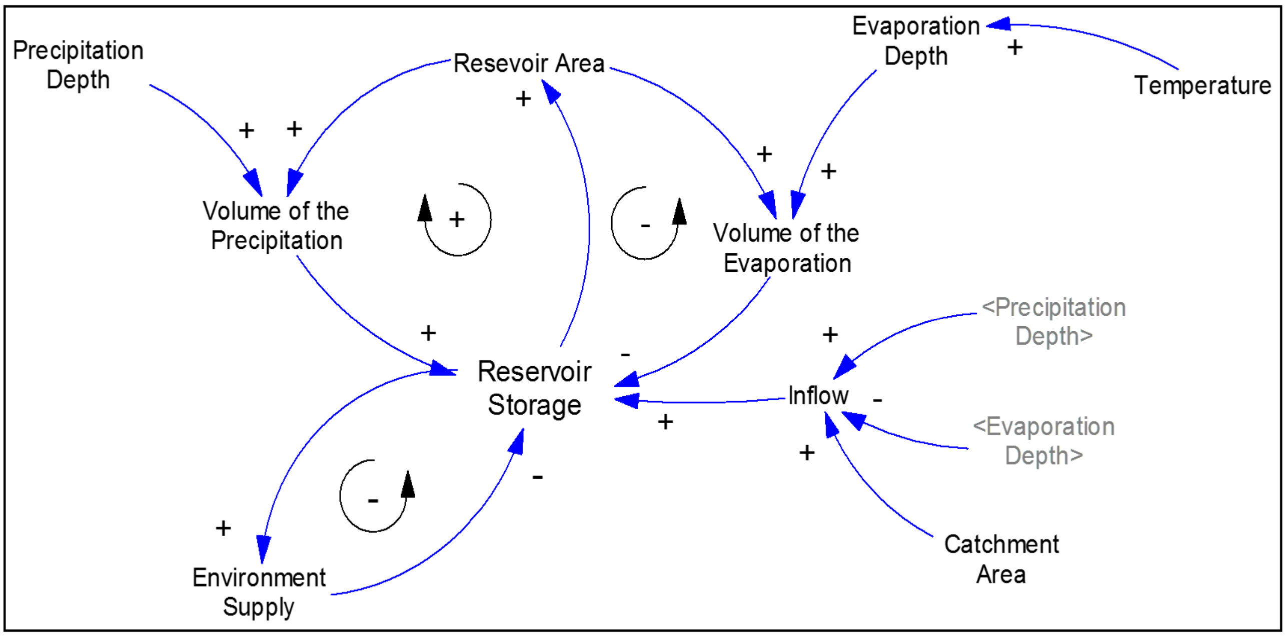

Figure 3.8: Some dynamic mechanisms in the environmental sub-system.

Figure 3.9 shows that water allocation to industry, agriculture, and urban centers decreases the water availability, and is a source of balancing behavior in the system. On the other hand, allocating more water to agriculture causes an increase in crop production, and then it leads to more irrigation water demand and it means more water requirement. Thus, in this case water allocation generates a growth dynamics in the system.

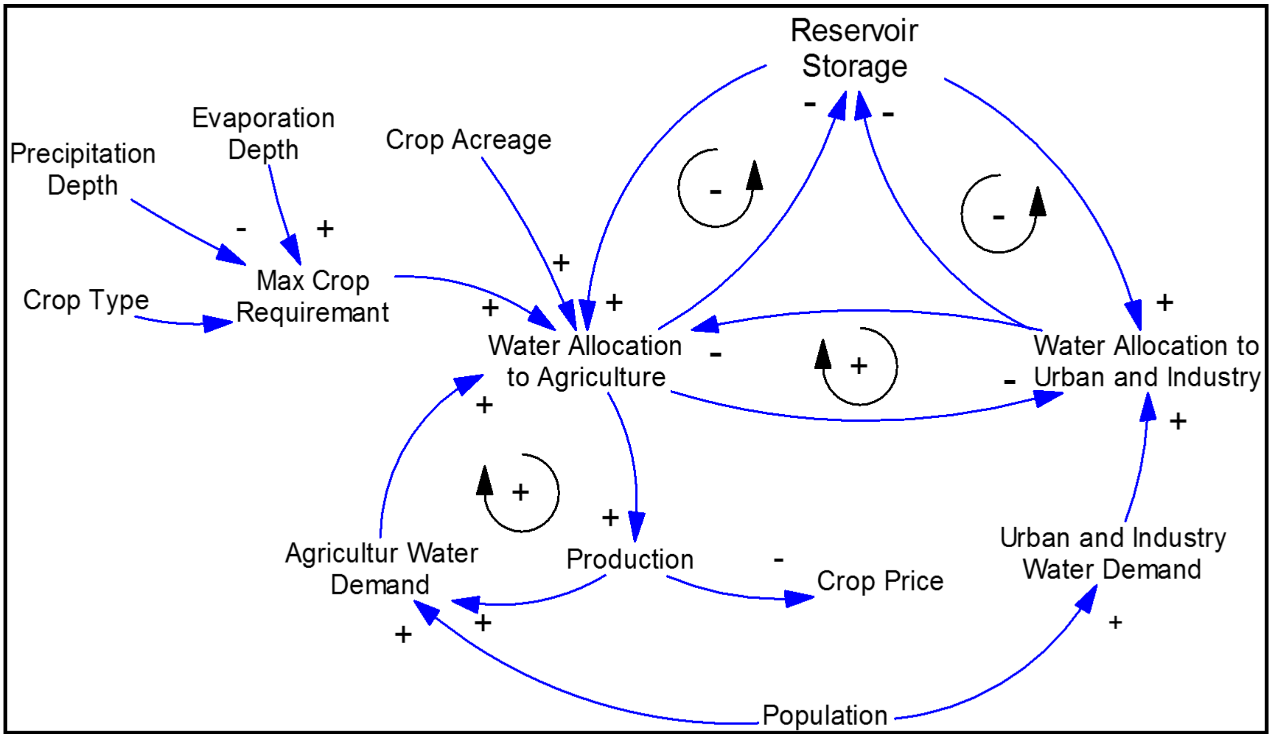

Figure 3.9: Some dynamic mechanisms in the human sub-system

After creating feedback loop diagrams, they will be quantified in a stock-flow diagram. In this research, flow variables were applied to model water allocation to each sector, as well as evaporation, and precipitation. Stock and flow variables are typically used to model water storage and water inflowing in/to a reservoir, respectively. Other water components can be represented by auxiliary variables and connectors are applied to indicate the interactions of components to each other.

3. 4. An IWRM Model using SD Approach ($SWAMP_{OM}$)

$SWAMP_{OM}$, implemented using the system dynamics (SD) approach, follows the SWAMP framework proposed by Hassanzadeh et al. (2014). $SWAMP_{OM}$ comprises a water allocation model and economic evaluation, instream flow needs, and dynamic irrigation demand sub-models. The water allocation model is an emulation of Water Resources Management Model (WRMM) and the dynamic irrigation demand and economic evaluation sub-models are developed using the same approach used in the $SWAMP_{SK}$ model (Hassanzadeh et al., 2014).

Input data (water demand and water supply) and operating policies (penalty zones) required to make the water allocation model are derived from the WRMM input files. Like WRMM, each water user receives the water based on its specific weekly demand; but, the penalty zones in WRMM only specify the priority of the users to receive the water in the $SWAMP_{OM}$'s water allocation model. A user with a higher penalty obtains the water first. As mentioned in previous sections, there is one important hydropower plant in the basin and it has the highest priority after minor units. According to WRMM's penalty values, some irrigation districts, most of which are private, ranks as third in water allocation order, and afterwards instream flow need (IFN) receives the water (Alberta Environment, 2010). To allocate water to users, it is assumed that each user gets the water from the nearest river (in the case of tributaries) or river reach (in the case of main river abstractions). If the nearest river reach cannot meet the entire demand, the next upstream reach is responsible to provide the water. When all rivers, which can allocate the water to the user, do not have enough water to satisfy the demand, the nearest reservoir releases the water to meet the rest of the user's demand. All water components and water supplies modeled in $SWAMP_{OM}$ are shown in figure 3.3.

3. 4. 1. Water Allocation Model

In this section how water is allocated to each component in the OMRB's water system will be described in detail. As can be seen in figure 3.3 and 3.10, red fletchers indicate minor units to which water is allocated first. Minor units, located before the Oldman reservoir, receive water only from the nearest river. As an example, minor 609 (a small town with senior water right in receiving water) only gets water from the Castle River (Figure 3.10). Water is allocated to some minor units only by reservoirs such as minor 212 and minor 215.

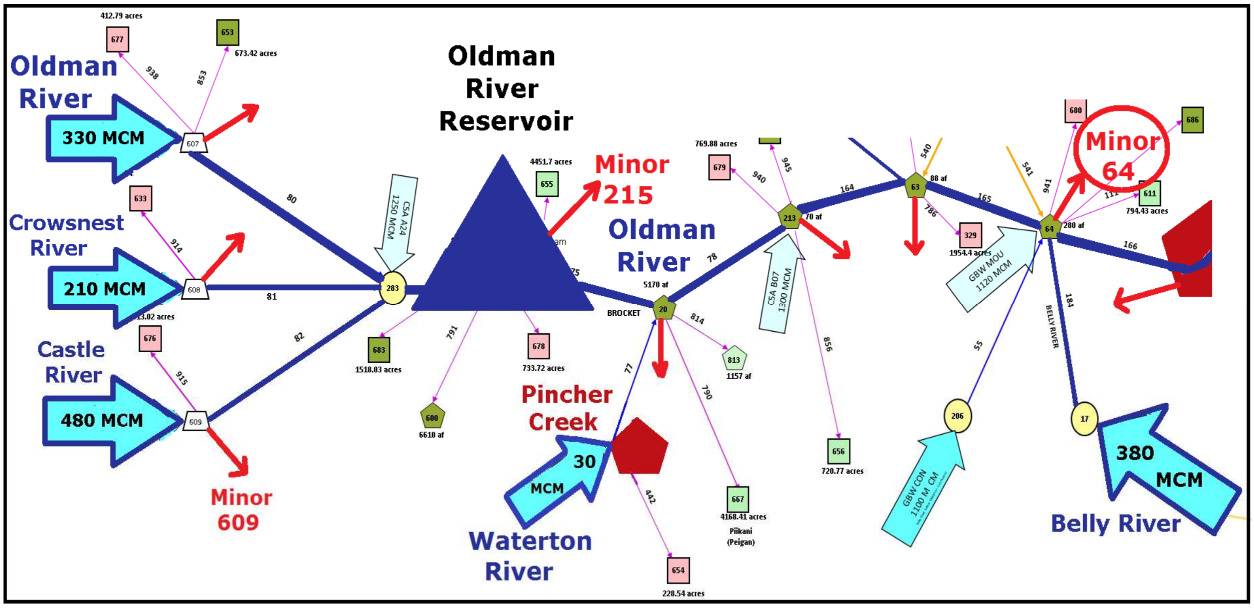

Figure 3.10: Schematic map for the minor units in the OMRB system.

For other minors water allocation is complicated, therefore, it will be thoroughly explained for minor 64 (a small town near Lethbridge), as an example. Minor 64 first receives water from the Belly River (Figure 3.10). If this river cannot meet the entire minor 64's demand, the remaining demand will be satisfied by the next upstream river, Waterton River. If its demand is not entirely met, then three next upstream rivers (Oldman, Castle, and Crowsnest Rivers) are assumed to provide the water needed for minor 64. In this stage the amount of water, which is allocated from each river, is computed based on water flowing in that river in each modeling time step (one week). This technique will be called the shared method. For example, if 6, 4, 5 MCM of water flow in the Oldman, Castle, and Crowsnest Rivers, respectively in a specific week, $\frac{6}{6+4+5}$ of minor 64's remaining demand is assumed to be met by the Oldman River, $\frac{4}{6+4+5}$ of demand by the Castle River, and $\frac{5}{6+4+5}$ of demand by the Crowsnest River. Since minor 64 is located downstream of the Oldman Reservoir, it must receive water directly from the reservoir, not from the upstream rivers. Therefore, the summation of $\frac{6}{6+4+5}$, $\frac{4}{6+4+5}$ and $\frac{5}{6+4+5}$ of minor 64's remaining demand is satisfied by the reservoir.

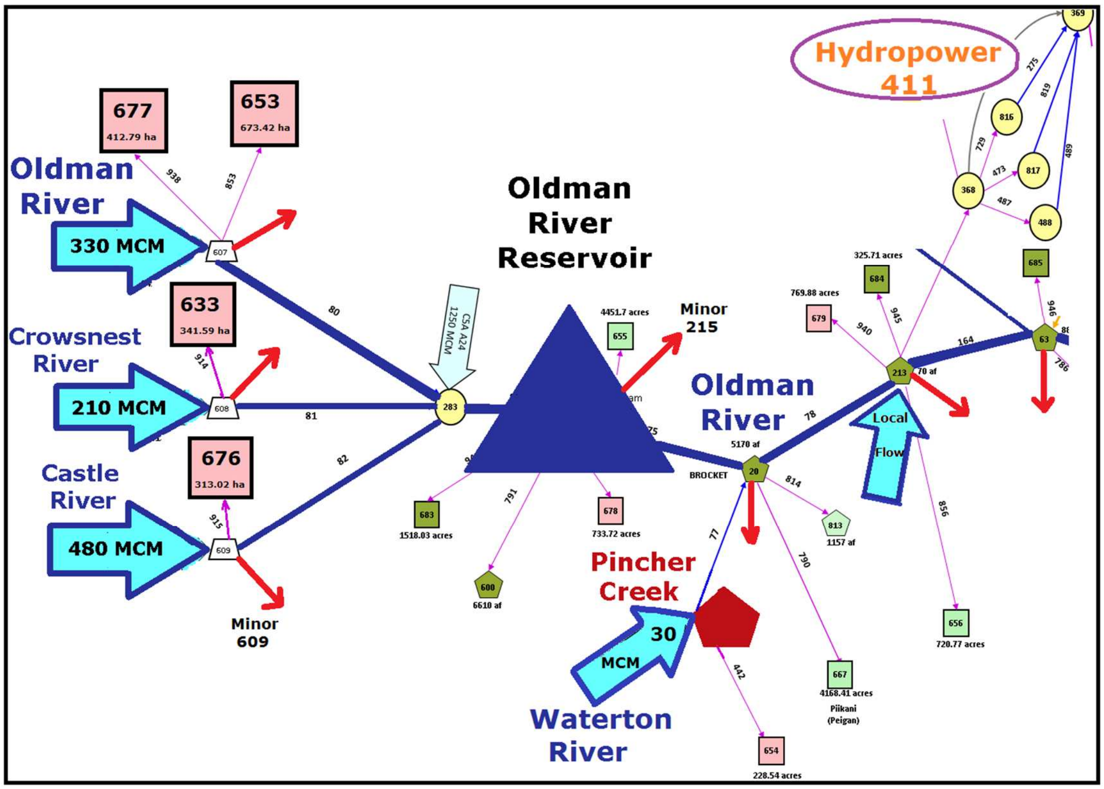

Figure 3.11: Schematic map of the hydropower plant within the OMRB.

The hydropower plant, which has second highest priority, receives water in the same way as the minor 64 (Figure 3.11). A local river followed by the Waterton River allocates water to hydropower. If its demand is not satisfied, the shared method is applied to calculate the amount of water that is supposed to be supplied by each upstream river (Oldman, Castle, and Crowsnest

Rivers). Afterwards, the rivers' shares of the demand are summed and provided by the Oldman Reservoir, as for minor 64.

After minors and hydropower plant, four irrigation fields located in the upstream of the Oldman Reservoir rank as third in water allocation order. They have been depicted with large pink squares in figure 3.11. Two of them receive water from the Oldman River, one of them from the Castle River and the last One from the Crowsnest River. After subtracting water allocated to the minors and the hydropower plant from water flowing in these three rivers, the amount of water remaining in each river is calculated. Then, the remaining water is considered to allocate water to irrigation fields. The rest of water flowing in three rivers goes to the Oldman River Reservoir.

Some irrigation fields, most of which are private, receive water in the fourth order. These fields, located downstream of the Oldman Reservoir, get water from the nearest rivers. If the nearest rivers cannot meet the entire demand, the Oldman Reservoir is responsible to provide the water.

In many reaches of the Oldman River, flow regulation and water use have a negative effect on fish habitat, riparian vegetation (cottonwood forests), and water quality (AMEC, 2009). To protect the natural aquatic ecosystem, a specific amount of water is considered to allocate to the ecosystem which is called instream flow need (IFN). WRMM uses a fish rule curve (FRC) method to calculate IFN for each river in the OMRB (This method will be briefly explained in section 3.4.4). Each section of each river in the OMRB has specific IFN that should be met. The Oldman River, as an example, has six sections, with a different IFN (Figure 3.12). To meet the IFN of a specific section, first the amount of water, which is allocated to the downstream minor units, hydropower plants, and private irrigation fields and passes through that specific section of the river, is calculated. Afterwards, this amount of water is subtracted from the IFN of the section and the remaining IFN is computed. Like other mentioned water users, the remaining IFN is first satisfied by the nearest rivers or river reaches, and then the Oldman River Reservoir provides the water.

The last water users to receive the water are the rest of irrigation fields and major units. These users follow the method applied to the private irrigation fields to meet their demand.

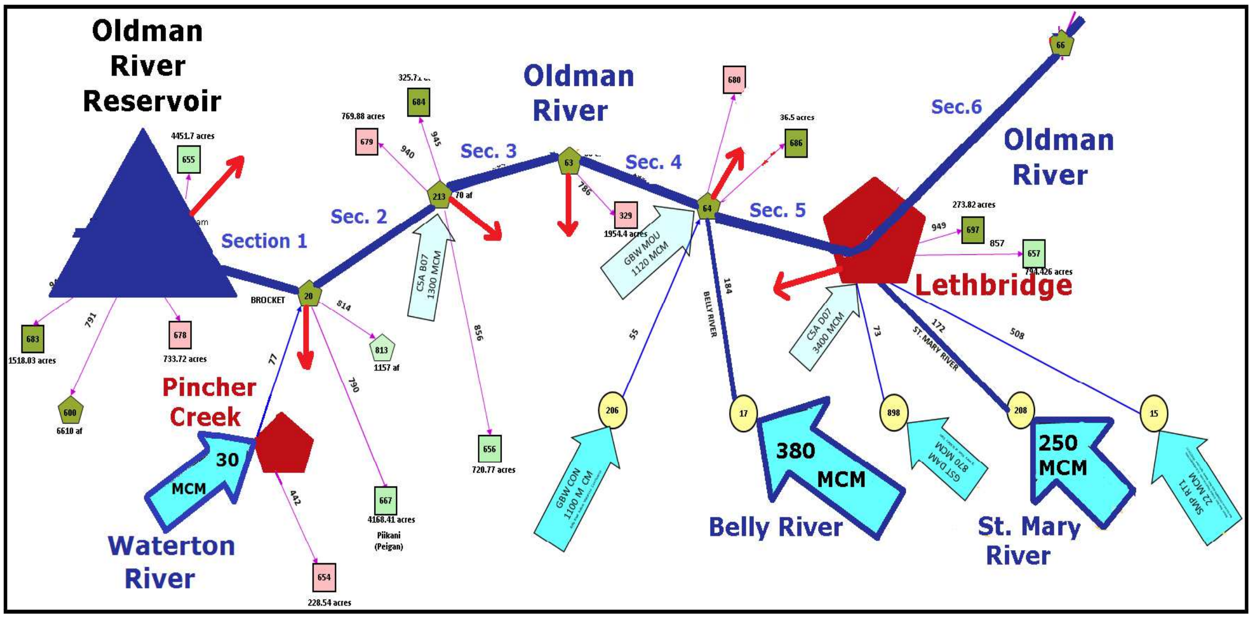

Figure 3.12: Different sections of the Oldman River

Reservoir Operation: To release the water from the reservoir, two penalty zones, indicating the physical maximum and minimum storage zones have been considered. The reservoirs may have additional penalty zones for active storage (Ilich, 1992). The penalty zones and the downstream users' water demand (which is not met by the downstream rivers) and the downstream users' penalty control the amount of water released from the reservoir. To estimate the amount of water stored in the reservoir, the mass balance equation is used (equation 3.2).

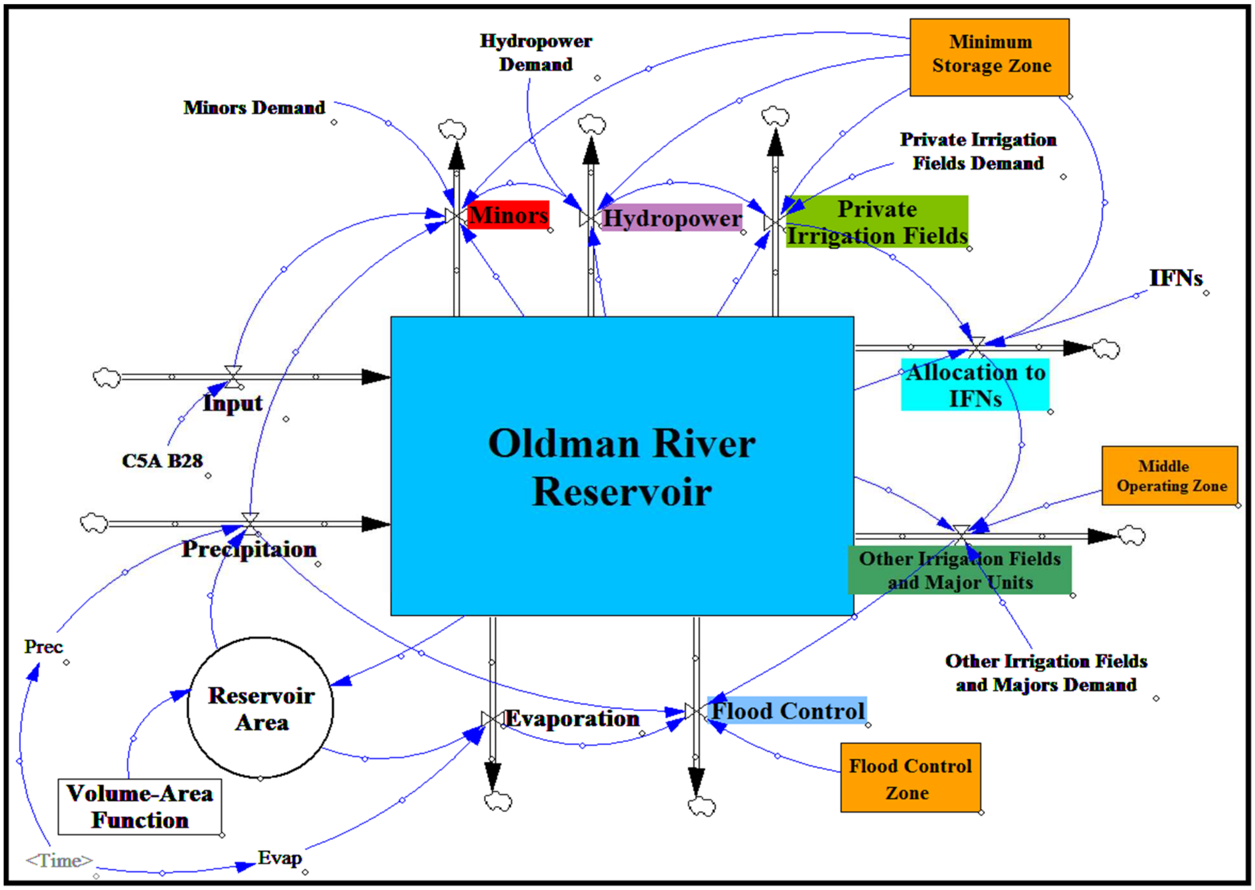

Figure 3.13: Stock-flow diagram for the Oldman river Basin

How a reservoir is operated in the $SWAMP_{OM}$ is precisely explained below for the Oldman River Reservoir, as the biggest and most complicated reservoir operated in the basin. Figure 3.13 shows a simplified stock-flow diagram (SFD) for the Oldman River Reservoir. Each flow fletcher indicates the amount of water released/entered from/ to the reservoir. The orange auxiliary variables indicate the operating zones of the reservoir. The Oldman reservoir has three orange auxiliary variables, hence, three operating zones have been applied to operate it. Minimum storage zone represents the weekly minimum storage capacity, flood control zone indicates the weekly maximum water stored in the reservoir to avoid flooding, and middle operating zone works to assign the amount of water released for some irrigation fields and major units.

Minimum storage capacity of the Oldman Reservoir, representing a water level of 1065 m in each week, and the flood control level have the highest priority in the whole OMRB water system. Therefore, the amount of water between these two levels can be allocated to the minors, hydropower, private irrigation fields, and IFNs which have less priority than these two levels. Among these four users, minors first receive the water, followed by hydropower and private irrigation fields. IFNs rank as fourth in water allocation order. After these users, minimum storage, and flood control zones, the highest priority belongs to the middle operating zone. The water level of the reservoir for this zone is 1112 m for each week. This zone works for water allocation to some irrigation fields and major units, because their priorities are less than the middle operating zone. Therefore, the $SWAMP_{OM}$ prefers to store the water by this level, rather than allocate it to some irrigation fields and major units. The amount of water more than the middle operating zone can be allocated to these users. After allocating water to all users, if the water stored in the reservoir was more than the flood control operating zone, then the extra water is released via flood control flow fletcher. Figure 3-14 shows the Oldman reservoir operating zones.

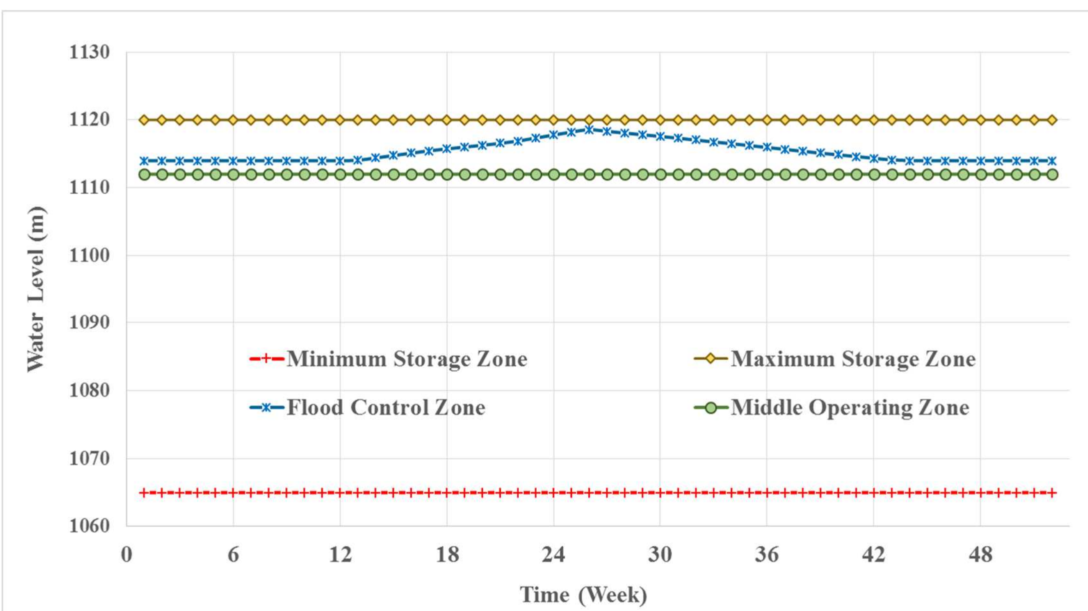

Figure 3.14: The Oldman River Reservoir operating zones

3. 4. 2. Dynamic Irrigation Demand Sub-model

The dynamic irrigation demand sub-model calculates the amount of water required by the main crops (alfalfa, wheat, barley, corn, canola, flax, potato, sugar beet, and beans) planted in the OMRB, which cannot be provided by rain and should be met by irrigation for each week for each irrigation district. This amount of water is called the crop irrigation water demand (CIWD). To estimate the CIWD, first of all, crop water requirements, which are a function of reference evapotranspiration (ET_0) and crop coefficient (K_C) should be computed. The sub-model applies the modified Penman equation to calculate the reference evapotranspiration (AIMM, 2006). The meteorological data required in the modified Penman equation includes mean daily temperature, dew point temperature, solar radiation, wind speed, and station elevation. Then, the ET_0 is determined by (ASCE, 2005):

$$ET_0 = \frac{\left(0.408\times\Delta\times(\mathrm{Rn}-\mathrm{G})\right)+\gamma\times\left(\frac{1600}{T+273}\right)\times u_2\times(es-ea)}{\Delta+(\gamma\times(1+0.38\times u_2))} \tag{3.4}$$

where Δ is the slope of the saturation vapor pressure-temperature curve (kPa/^{o}C), Rn is the net radiation (MJ/m^2/day), G is the soil heat flux (MJ/m^2/day), γ is the psychrometric constant (kPa/^{o}C), T is mean daily temperature (^{o}C), and u_2 is the wind speed at the height of 2 m (m/s). Then, the crop water requirement (CWR) (mm) is equal to (ASCE, 2005):

$$CWR=ET_{max\ c} = ET_0 \times K_C \tag{3.5}$$

K_C is different for each crop and in each stage of crop growth. The stages of crop growth are divided into four stages comprising an initial stage, a development crop stage, a mid-season stage, and an end of the late season stage. In the initial stage, the K_C is constant, but it gradually increases in the development stage, until reaching the maximum value in the mid-season stage.

Then, it decreases in the late season stage.

Soil moisture (SM_t) is the second variable affecting the crop irrigation water demand and it was determined for each crop in each irrigation district. The factors affecting the soil moisture in each week encompass initial soil moisture at the beginning of a week (SM_{t-1}), precipitation (P_t) including rainfall, snowfall, actual evapotranspiration (Eta_t), irrigation water supply (IWS_t), deep percolation (DP_t), and the amount of water running off (R_t). The soil moisture at the end of each week (mm) will be computed by the balance equation (Baier and Robertson, 1966):

$$SM_t = SM_{t-1} + P_t + IWS_t - Eta_t - DP_t - R_t \tag{3.6}$$

The initial soil moisture was assumed to be equal to field capacity for each crop in the first week of planting because crop planting typically starts in May when the soil is wet enough due to snowmelt. Three phases of precipitation, changing the soil moisture, are considered and comprise snow, rainfall with the intensity less than 25 mm, and intense rainfall which is more than 25 mm in the week. If the average temperature is less than zero, the precipitation falls in the form of snow. Otherwise, the phase of precipitation is rainfall. When the intensity of rainfall is less than 25 mm, it is assumed to infiltrate into the soil. But, a part of intense rainfall (more than 25 mm) contributes to runoff (R_t) and the rest (IR_t) infiltrates into the soil.

Actual evapotranspiration for each crop (ETa_t) is a function of the crop water requirement ($CWR_{t,c}$), permanent wilting point of crop c ($PWP_{t,c}$), field capacity of crop c ($FC_{t,c}$), and soil moisture ($SM_{t,c}$) and equals:

$$ETa_t = CWR_{t,c} \times \frac{SM_{t,c} - PWP_{t,c}}{FC_{t,c}} \tag{3.7}$$

Crop irrigation water demand ($CIWD_t$) is approximated based on crop water requirement ($CWR_{t,c}$), soil moisture ($SM_{t,c}$), permanent wilting point of crop c ($PWP_{t,c}$), field capacity of crop c ($FC_{t,c}$), as well as irrigation efficiency of each irrigation district (IE_{id}). The dynamic irrigation demand sub-model tries to keep soil moisture between permanent wilting point and field capacity in the root depth of the crop, while meeting the crop water requirement in each week. Therefore, $CIWD_t$ is equal to (AIMM, 2006):

$$CIWD_t = \frac{\mathrm{CWR}_{t,c} - SM_{t,c} + (FC_{t,c} + PWP_{t,c})/2}{\mathrm{IE}_d} \quad (3.8)$$

The equations applied to calculate Δ, Rn, u2, γ, R_t, and IR_t, are explained in Appendix A.

3. 4. 3. Instream Flow Needs Sub-Model

So far, instream flow needs (IFN) for the Oldman River Basin have been calculated using a fish rule curve (FRC) method, which meets the local minimum flow requirement for fish habitat (AMEC, 2009). The FRC method calculates IFN based on the weighted usable area (WUA) of the river as a function of the discharge (WUA curve) and the available natural supply of water. The wetted usable area of a river is defined based on its suitability for use by aquatic organisms (Clipperton et al., 2003). In this method IFN changes depending not only on the WUA curve, but also on the hydrologic conditions (wet, dry, average) during a specific period (Clipperton et al., 2003). WRMM applies the IFN determined by FRC method. In WRMM different sections have been defined for each river and each section has a specific IFN. In the first stage of modeling, these data were used as the instream flow needs in $SWAMP_{OM}$.

Recently, Alberta Environment has been using a new method, the Alberta Desktop Method (ADM), which requires weekly/monthly naturalized hydrological data, to determine the environmental flows (Locke and Paul, 2011). This has been applied in this thesis. In this method, first an ecosystem base flow (EBF) component is calculated, so that a percent exceedance natural flow is set as the EBF for each week. A percent exceedance natural flow is defined as a percentile of ascendingly sorted data. An 80% exceedance natural flow, as an example, can be calculated by sorting historical, naturalized data for each week, and then computing the 80% percentile of the data, and setting it as the EBF. The amount of water flowing in the river should not be less than the EBF. This exceedance value is different for each section in each river in the OMRB (Table 3.1). The Oldman River, for instance, has 6 sections whose exceedance values are specified in table 3-1 (Locke and Paul, 2011).

Table 3.1: Percent exceedance natural flow for some rivers in the OMRB

River	Section	Percent Exceedance Natural Flow
Oldman River	1	89
	2	80
	3	88
	4	89
	5	88
	6	89
Belly River	1	81
	2	80
St. Mary River	1	88
Waterton River	1	81

After determining the EBF, a percent of weekly natural flow is allocated to the IFN. Table 3.2 shows these percentage values for the OMRB's rivers. Then, the EBF and the percent of weekly natural flow criteria are combined, so that the percent of weekly natural flow (60% of weekly natural flow for the section 1 of the Oldman River, as an example) is compared with the EBF. Then, if this flow in a specific week was less than the EBF (89% of exceedance natural flow for the section 1 of the Oldman River), the EBF in that week is set as the IFN; otherwise the percent of weekly flow is used.

Table 3.2: IFN percent of natural flow component for some rivers in the OMRB

River	Section	Percent Of Natural Flow Component
Oldman River	1	60
	2	70
	3	85
	4	70
	5	80
	6	80
Belly River	1	70
	2	80
ST. Mary River	1	60
Waterton River	1	80

3. 4. 4. Economic Evaluation Sub-Model

The major economic benefit in the basin from water management is earned by agriculture (to which 88% of the water supply is allocated) and it is computed by annual crop yield multiplied by their costs and revenues per ton (Hassanzadeh et al., 2014). Annual crop yields are determined by the FAO (2002) methodology:

$$Y_{ac} = Y_{max\ c}(1 - \sum_{t=1}^{n} Ky_t \times (1 - \frac{ETa_{c,t}}{ETmax_{c,t}})) \qquad (3.9)$$

where $Y_{max\ c}$ and Y_{ac} are the annual maximum and actual yields (Ton/(Year*ha)), $ETmax_{c,t}$ and $ETa_{c,t}$ are the maximum (crop water requirement) and actual evapotranspiration (mm), Ky_t is a yield response factor and n is the number of weeks in the growing season in a year. The production cost for each crop includes costs of seeds, fertilizer, fungicide, insecticide, herbicide, hired labor, equipment fuel, pumping, property taxes, and crop insurance. Therefore, the annual economic benefit of planting each crop (TEB_{ac}) in the basin is approximated by:

$$TEB_{ac} = (Y_{ac} \times \ Crop\ Total\ Area\ (ha) \times Crop\ Market\ Price\ (\$/Ton)) - (Crop\ Production\ Cost\ (\$/(ha * Year)) \times \ Crop\ Total\ Area\ (ha)) \quad (3.10)$$

The total irrigation area in the OMRB is about 123,420 ha. $SWAMP_{OM}$ uses the crop market prices and production costs in 2006 to calculate agricultural economic benefit from 1928 to 2001. The second source of water-based economic benefit in the OMRB is hydropower. Annual hydropower Generation (MWh) multiplied by revenue and cost results in economic benefit from this sector. Annual hydropower generation (MWh) (P) can be calculated by

$$P = \frac{Q \times (H - HL) \times TE \times GE \times 9.907}{1000} \quad (3.11)$$

where Q is flow in hydropower channel (m^3/s), H is the average head available for power generation (m), HL is the head loss at the rated head and flow (m), 9.907 is a coefficient of changing units to metric, and TE and GE are turbine and generator efficiencies. Multiplication of generated hydropower (P) (MWh) by revenues results in economic benefit for this sector ($/MWh). Since there was no access to the market price of hydropower generation for the Oldman plant, the market price for the power generation in the Lake Diefenbaker Reservoir in 2010 is applied in this sub-model.

CHAPTER 4

RESULTS AND DISCUSSION

The results of the $SWAMP_{OM}$ model, including water allocation, economic evaluation, instream flow needs, and dynamic irrigation demand are separately provided in this chapter. Since $SWAMP_{OM}$ is an emulation of WRMM, its results are compared with those of WRMM. The impact of change in water supply and also a combination of changing water supply and the percent of natural flow component allocated to IFN on the basin's economy and water allocated to IFNs will be analyzed under different scenarios. Afterwards, a Pareto front approach is carried out in order to find the optimal sets of the Oldman Reservoir operating zones to evaluate trade-offs between optimal basin economic benefit, water allocation to IFN, and flood control. A brief description of this approach and its results will be discussed at the end of this chapter.

4. 1. Performance of Water Allocation Model

The water allocation model meets the water demand of one hydropower plant, 43 irrigation fields, 14 minor, 11 major units (minor and major units are municipal and industrial centers), and the instream flow need of 16 sections of different rivers in the Oldman River basin. The water resources to satisfy the demands are four big reservoirs, comprising the Oldman Reservoir, Pine Coulee Reservoir, Chain Lakes, Divpond, and 16 rivers and tributaries. Figures 4.1 and 4.2 show average weekly streamflow (1928-2001) of the main headwaters originating from the Rocky Mountain (Oldman, Castle, and Crowsnest Rivers) and tributaries emanating from Montana in the US (St. Mary, Belly and Waterton Rivers).

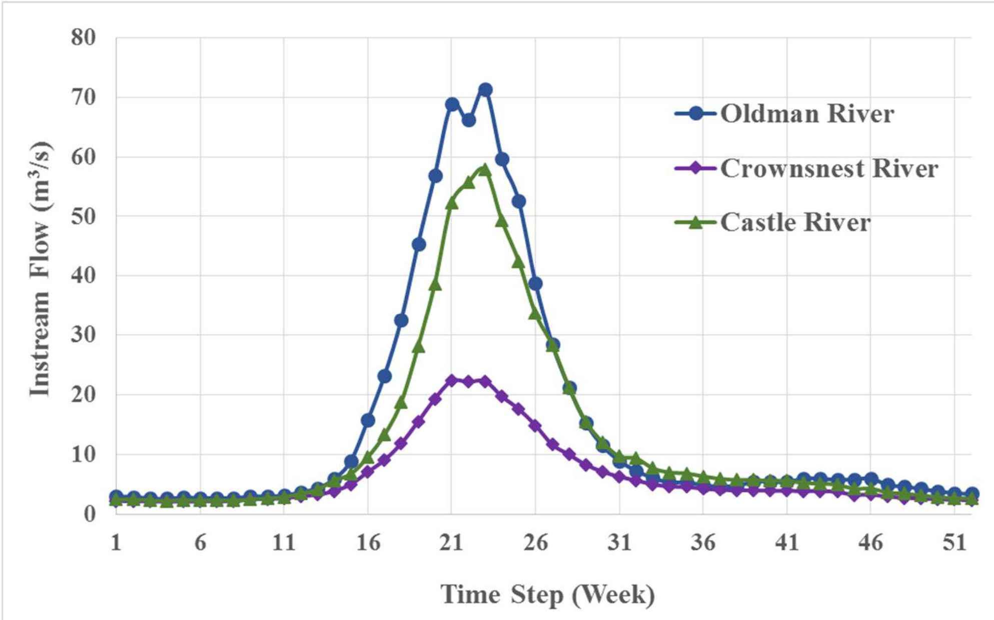

Figure 4.1: Average weekly headwaters flow originating from the Rocky Mountain

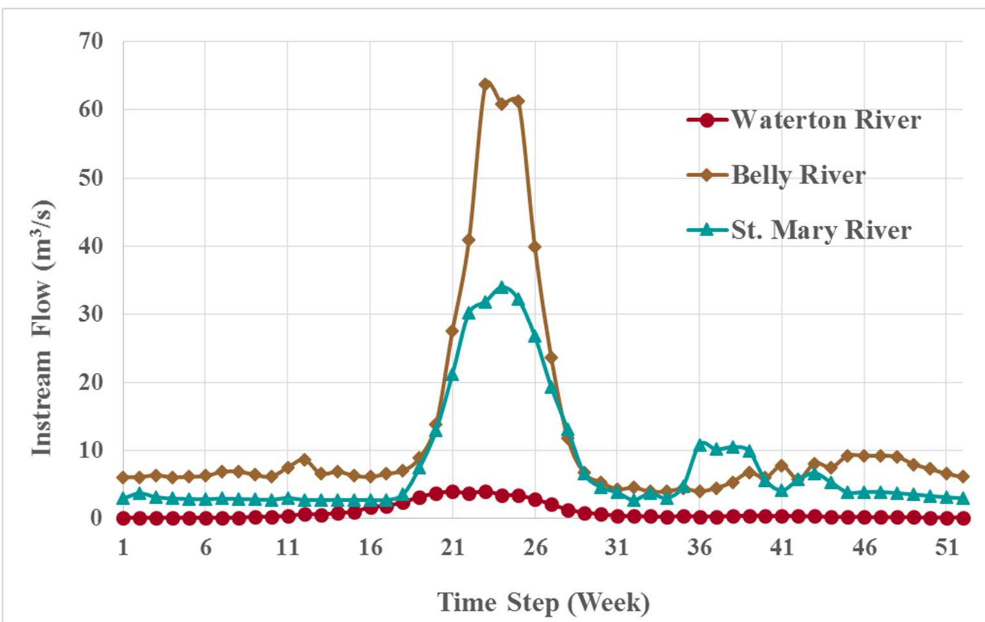

Figure 4.2: Average weekly rivers flow emanating from Montana, US

4. 1. 1. Water Allocation to Consumptive Water Components

As mentioned in chapter 3, minor units have highest priorities and their demand should be met before other users. Minor units typically have the lowest demands and the water allocation model could satisfy them even in dry years, as WRMM did. Figure 4.3 depicts the scatter plot of water allocated to all minor units by $SWAMP_{OM}$ versus that by WRMM on a weekly scale from 1928 to 2001.

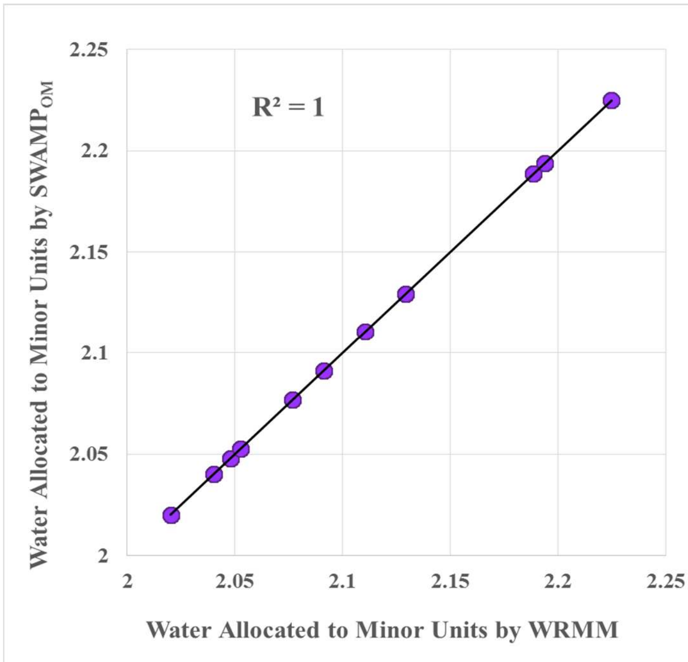

Figure 4.3: Water allocated to the minor units by $SWAMP_{OM}$ versus that by WRMM

Agriculture has a specific importance in the OMRB, and dominates the basin's water-related economy. $SWAMP_{OM}$ was used to model 43 irrigation fields in the basin (the same as WRMM), which belong to the Lethbridge Northern Irrigation District (LNID), St. Mary ID (SMID), Taber ID (TID), Ross Creek ID (RCID), and Private ID (PID). Since a large number of irrigation fields has been modeled, showing the performance of the $SWAMP_{OM}$ is difficult for all of them. Thus, the water allocated to each irrigation district is indicated. Figure 4.4 shows the scatter plot of water allocated to LNID by $SWAMP_{OM}$ versus that by WRMM on a weekly timescale from 1928 to 2001. Water allocated to LNID was completely matched to the WRMM results, excluding only 180 weeks (out of 3848 weeks), 16 of which were in 1988, a very dry year when the irrigation demand was very high (Figure 4.4b). For the LNID, R^2 between the WRMM's results and $SWAMP_{OM}$'s is 0.94.

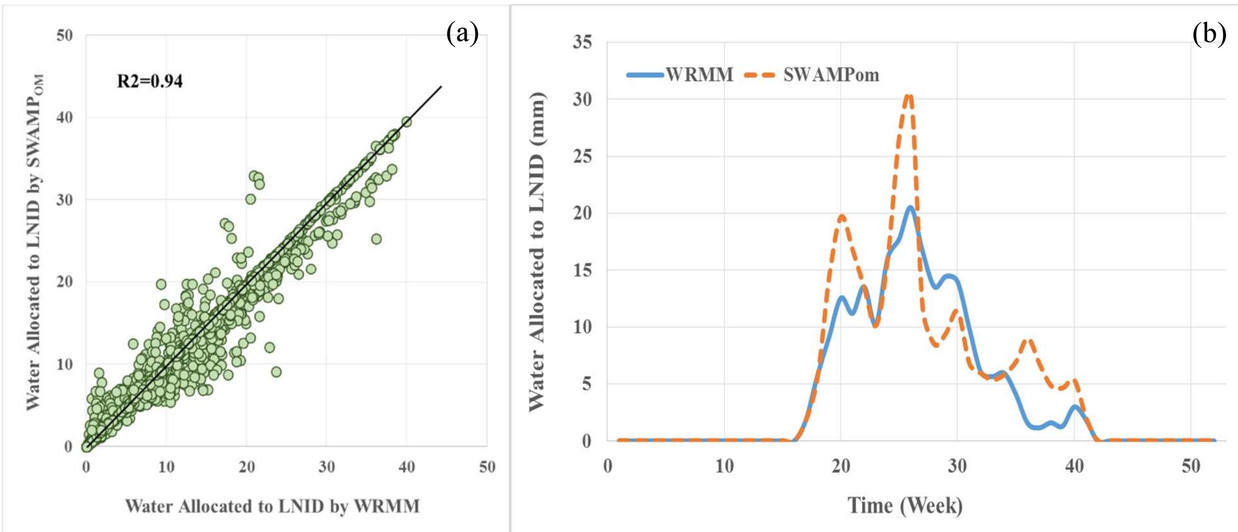

Figure 4.4: Water allocated to NLID by $SWAMP_{OM}$ and WRMM (a) and in 1988 (b)

For the PID, R^2 between the results of the two models is 0.89, and they were unmatched for 280 weeks, most of which occurred in the 1930's decade (Figure 4.5a). R^2 for the RCID and SMRID are 0.91 and 0.95, respectively (Figure 4.5b; c) and in both irrigation districts, water allocation by $SWAMP_{OM}$ has not been similar to that of WRMM in more than 250 weeks. 1931, 1941, and 1988 were the dry years when the results of WRMM and $SWAMP_{OM}$ were different. The R^2 between their results for the TID is lower than that for other irrigation districts and is 0.89 (Figure 4.5d). In more than 180 weeks the results of the two models are poorly matched and they occurred in 1931, 1944, 1977, 1988, and 2000.

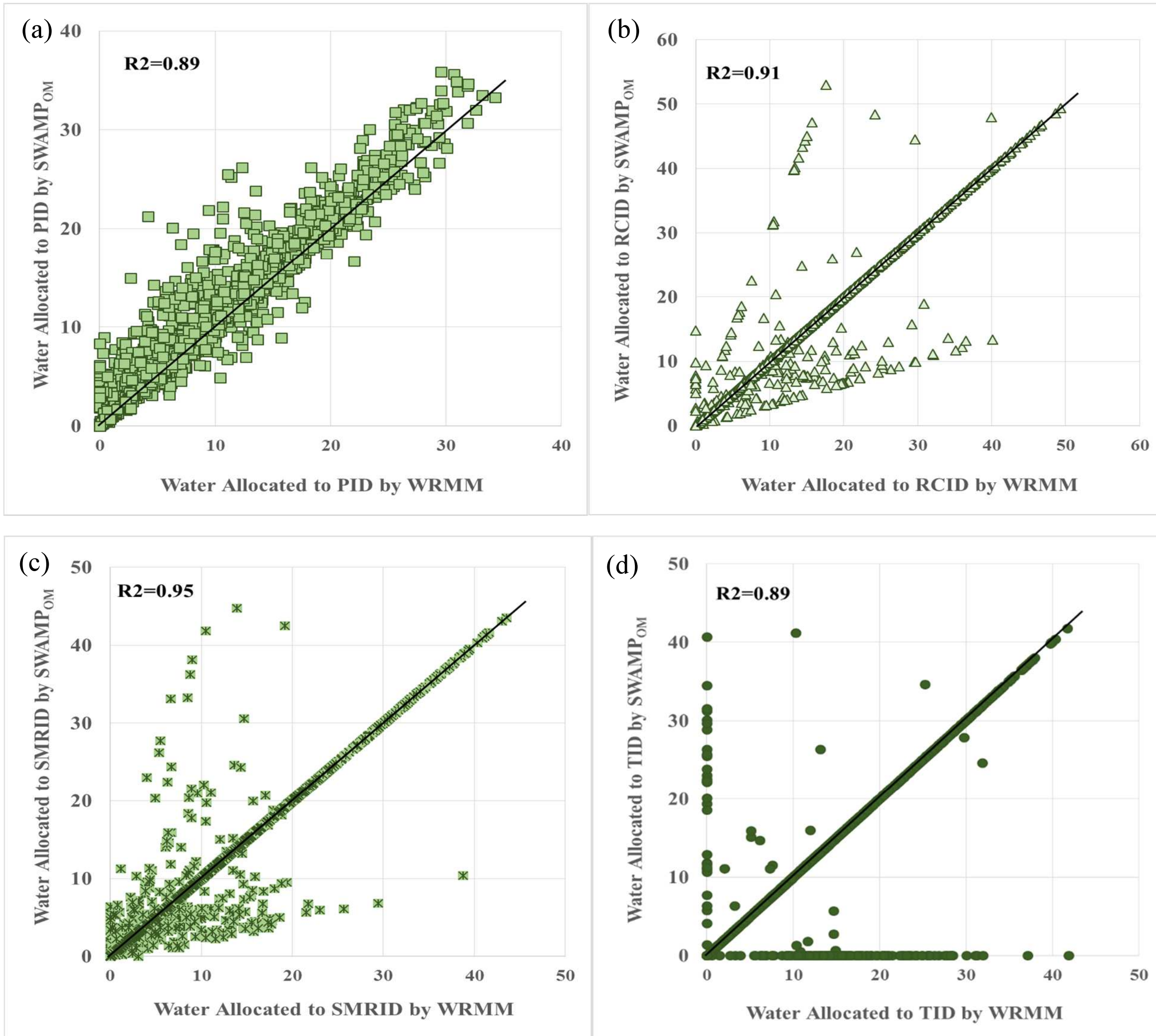

Figure 4.5: Scatter plot of water allocated to PID (a), RCID (b), SMRID (c), TID (d) by $SWAMP_{OM}$ and WRMM.

The main reason for the discrepancies in the performance of the two models is the treatment of penalty zones. In WRMM, 11 irrigation fields (IFs) have only one penalty zone, and the water allocation process is the same in WRMM and $SWAMP_{OM}$. Therefore, both models' results are completely matched for those irrigation fields. Figure 4.6 shows the scatter plot of water allocated to irrigation field 341 (a), and 324 (b), as an example of IF allocation by $SWAMP_{OM}$ versus that by WRMM. On the other hand, 32 other irrigation fields have four penalty zones, with values of

660, 661, 662, and 664. These penalties are very close together, hence have the same priority in water allocation simulation by $SWAMP_{OM}$. However, they are considered different in the optimization process in WRMM. Hence, both models represent a difference in outcome for these irrigation fields. Figure 4.7 shows the water allocated to irrigation field 341 (a), and 324 (b), as an example, by $SWAMP_{OM}$ versus that by WRMM.

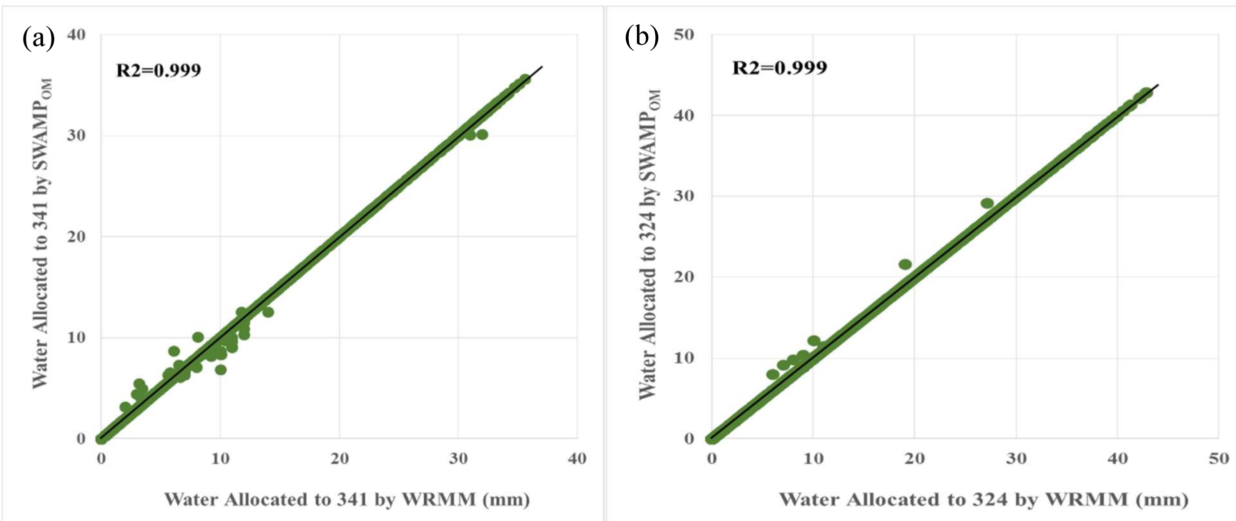

Figure 4.6: Scatter plot of water allocated to irrigation field 341 (a), and 324 (b) by $SWAMP_{OM}$ and WRMM.

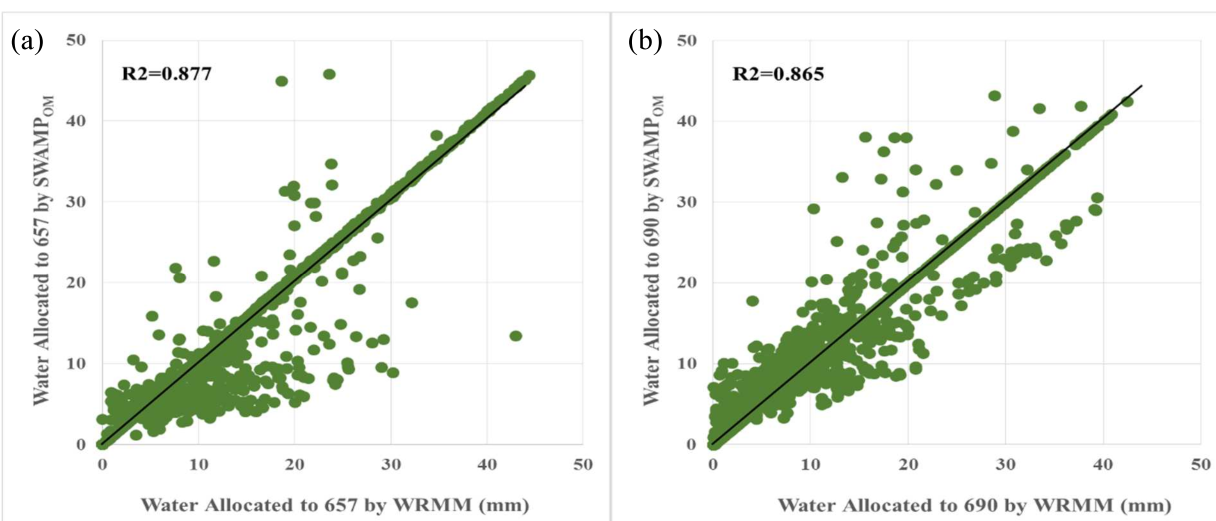

Figure 4.7: Scatter plot of water allocated to irrigation field 657 (a), and 690 (b) by $SWAMP_{OM}$ and WRMM.

Figure 4.8 shows the amount of water allocated to 11 major units by $SWAMP_{OM}$ versus that by WRMM. Major units rank last in water allocation order. The results of the two models are not totally matched and R2 is 0.77. In approximately 12% of weeks, the two models produced different results, mainly in the dry years. However, $SWAMP_{OM}$ allocates more water to the major units compared to WRMM. Each major unit in WRMM has four operating zones, which are very close together, thus all zones have the same priority in water allocation process in $SWAMP_{OM}$. This is the main reason for the difference between the results of the two models.

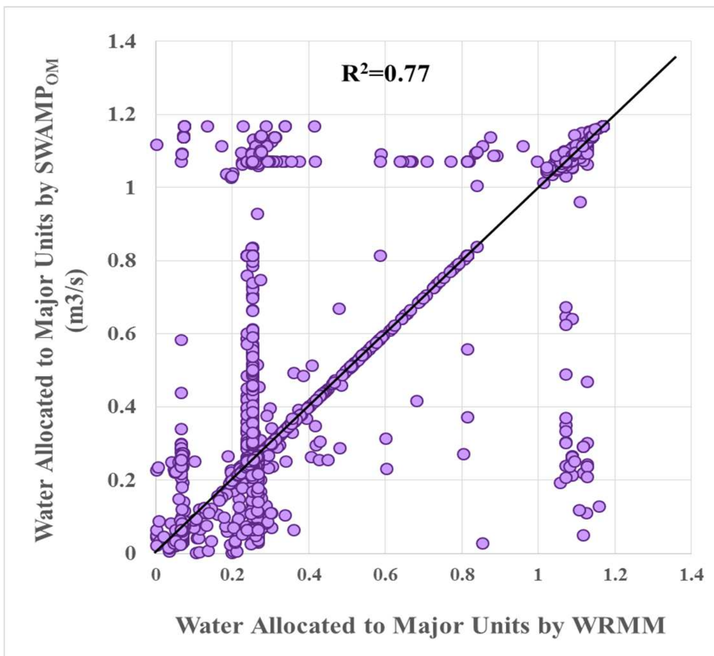

Figure 4.8: Water allocated to the major units by $SWAMP_{OM}$ versus that by WRMM

4. 1. 2. Water Allocation to Non-Consumptive Water Components

After providing the demand of the minor units, $SWAMP_{OM}$ is responsible to meet the hydropower plant's water demand which has the second highest priority. $SWAMP_{OM}$ met all hydropower weekly water demands from 1928 to 2001 (Figure 4.9); although WRMM could not meet it in some weeks, especially in 1931 (Figure 4.10). In that year, WRMM has only satisfied about half of the demand in four weeks (encircled points in figure 4.9), and more water has been stored in the Oldman Reservoir to allocate to some irrigation fields. However, $SWAMP_{OM}$ allocates more water to the hydropower plants, and therefore, other users with lower priority receive less water than the amount allocated to them by WRMM. The two models result in a small difference in water allocation to the hydropower plant, because two operating zones in WRMM, were translated into the same priority in $SWAMP_{OM}$.

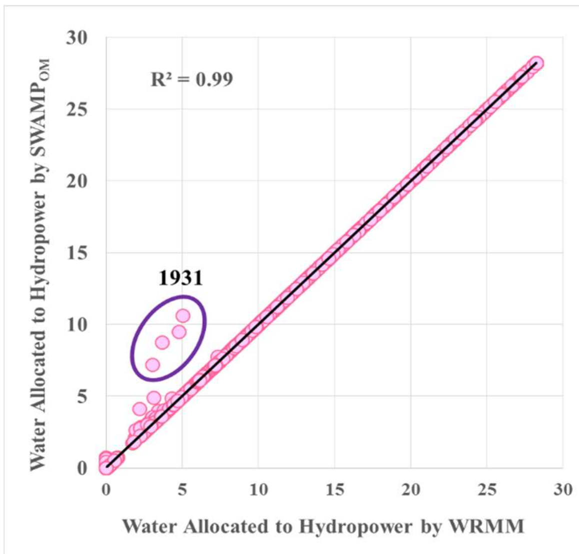

Figure 4.9: Scatter plot of water allocated to the hydropower plant by $SWAMP_{OM}$ and WRMM

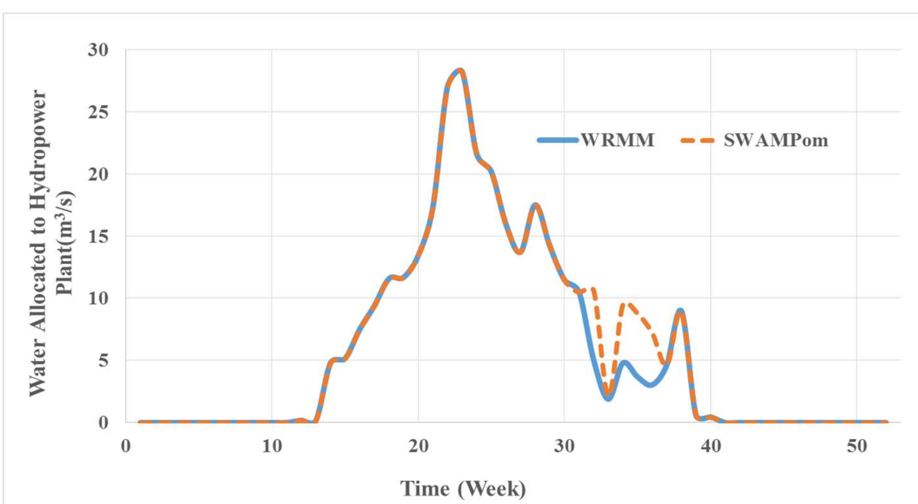

Figure 4.10: Water allocated to the hydropower plant by $SWAMP_{OM}$ and WRMM in 1931

$SWAMP_{OM}$ could satisfy instream flow needs -as the second highest priority to receive water among the non-consumptive water components- of the rivers, flowing in the OMRB, with results very close to the WRMM's. Figure 4.11 shows the comparison between the two models' results for the Willow Creek River (WCR, a), and the section 6 of the Oldman River (OMR, b), for instance. As can be seen in this figure, the results of the two models are fairly well matched, and R^2 is 0.987 and 0.979 for the Willow Creek River, and the section 6 of the Oldman River, respectively. In the low streamflow of the section 6 of the Oldman River, $SWAMP_{OM}$ allocated more water in comparison to WRMM.

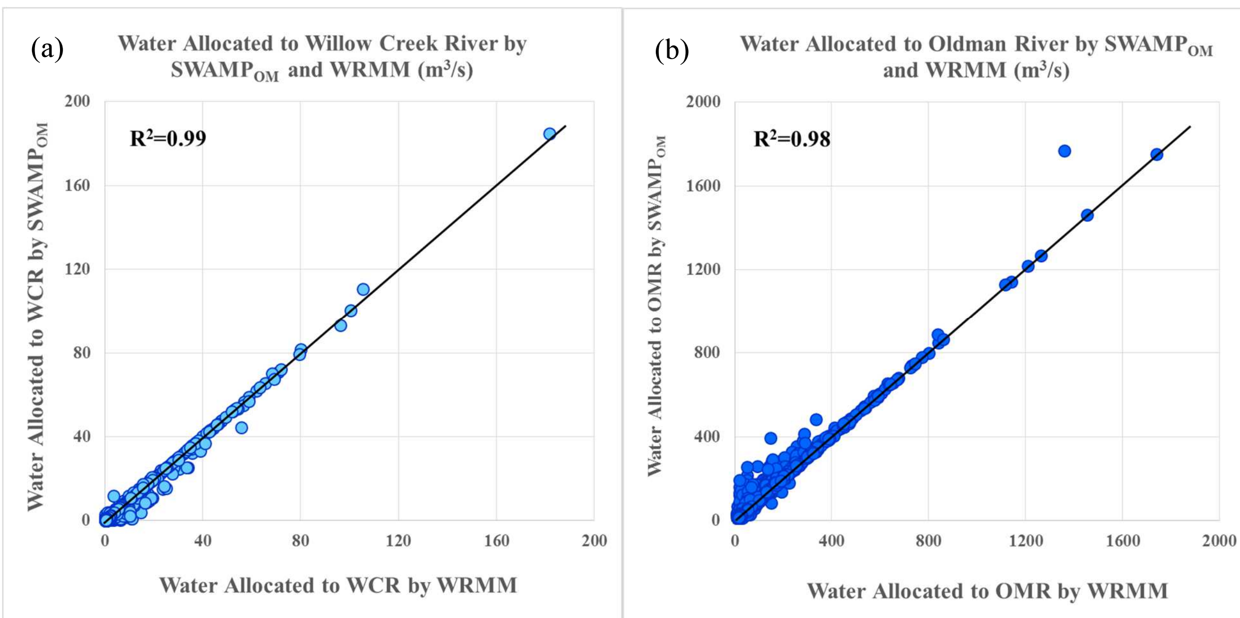

Figure 4.11: Water allocated to the Willow Creek River (a), and the section 6 of the Oldman River (b) by $SWAMP_{OM}$ compared to this by WRMM

Besides fulfilling the IFNs of the rivers, $SWAMP_{OM}$ should allocate 50% of natural flow to the Saskatchewan via the apportionment channel (figure 4.12), and meet the channel's demand. Figure 4.12 indicates that the results of $SWAMP_{OM}$ and WRMM are similar, with R^2 value of 0.992.

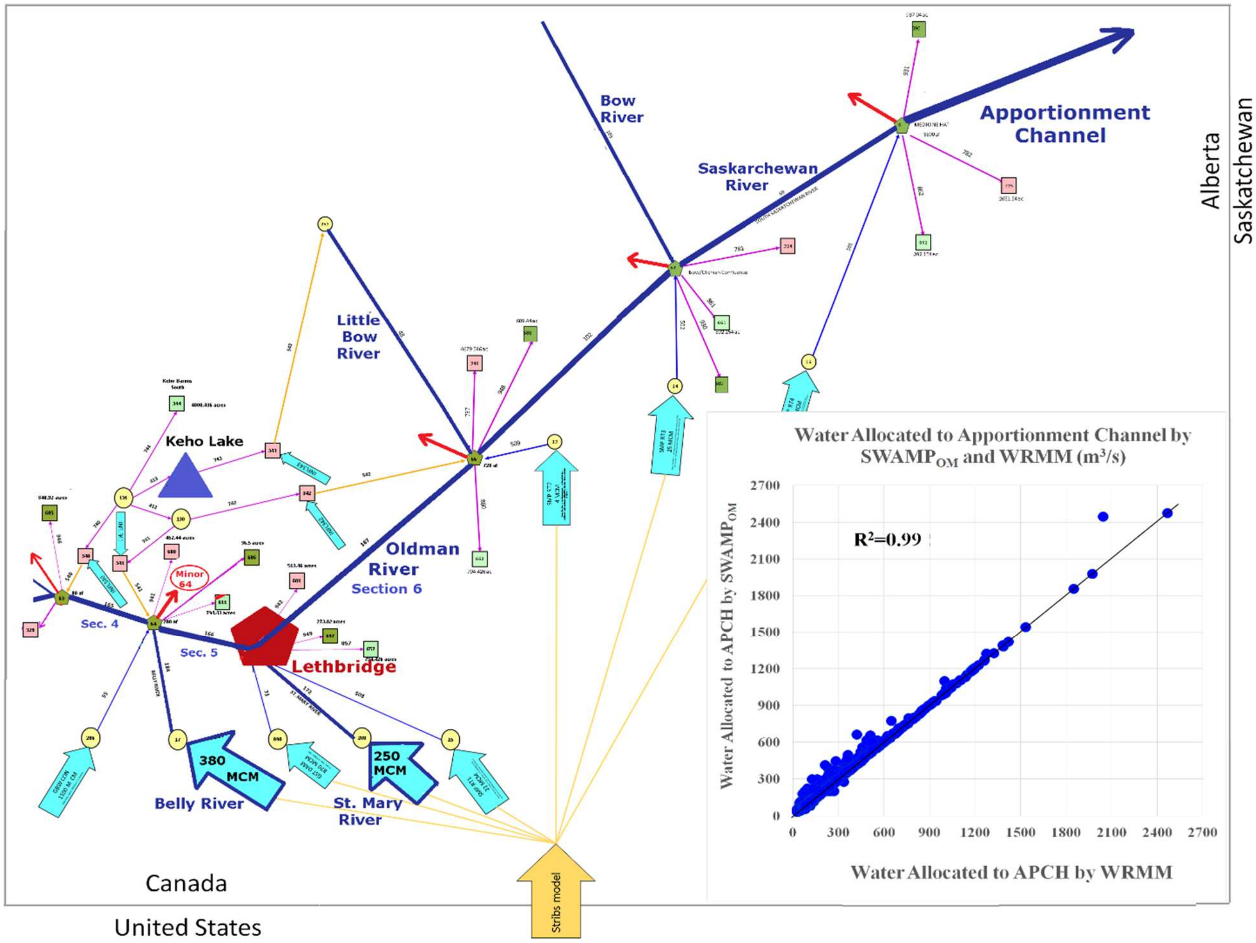

Figure 4.12: Water transferred via apportionment channel (APCH) by the $SWAMP_{OM}$ compared to that by WRMM

4. 1. 3. Performance of Reservoirs' Operation

The Oldman River Reservoir is the largest reservoir in the basin with a full storage capacity of 900 MCM. It has four important operating zones, and is operated based on these zones and downstream users' demands and priorities. Figure 4.13 illustrates the results of $SWAMP_{OM}$ and WRMM for the reservoir water level (a) and the amount of water released from the reservoir (b) from 1928 to 2001. There is significant correlation between the two model's results; R^2 is 0.97 and 0.95 for water level and outflow, respectively.

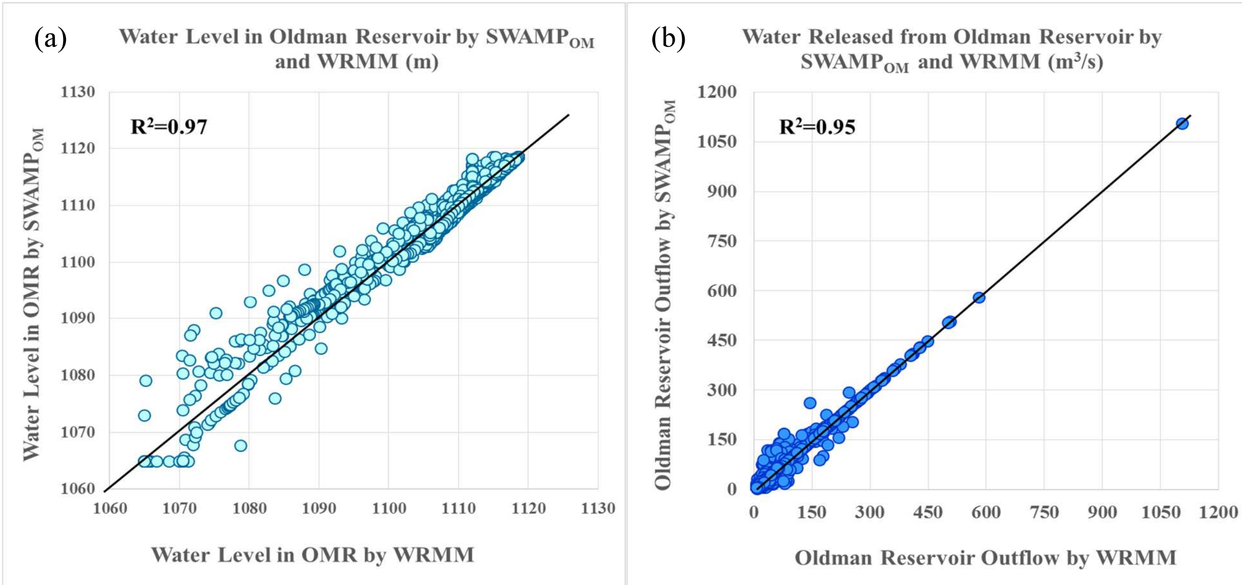

Figure 4.13: Scatter plot of the Oldman Reservoir water level (a) and the amount of water released from the reservoir (b) by simulating $SWAMP_{OM}$ and WRMM from 1928 to 2001.

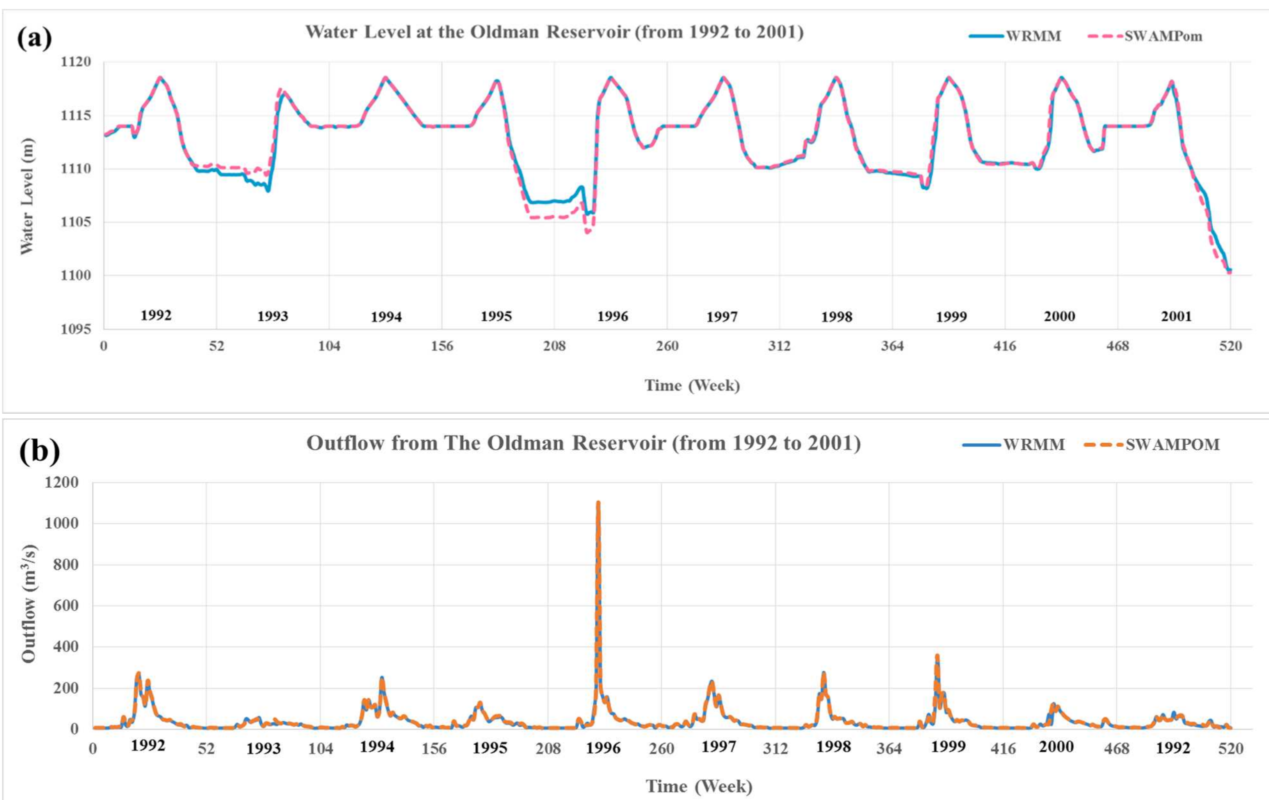

Figure 4.14: the result of WRMM and $SWAMP_{OM}$ in the Oldman Reservoir water level (a) and the reservoir outflow (b)

Figure 4.14 compares the results of the two models for the Oldman Reservoir water level (a) and the reservoir outflow (b). Since the Oldman Reservoir has been operated since 1991, the result of the two models from that year have been shown in this figure. The results of the two models for high reservoir water levels are completely matched, while there is a difference between outcomes of the two models in very low water level occurring in dry years.

For the Oldman River Reservoir water level and water released from the reservoir have been compared to the monthly historical data (figure 4.15). Water released from the reservoir is fairly well matched with historical data, while R^2 coefficient is only 0.68 for water level. As can be seen in figure 4.15, historical low flows (water released from the reservoir) have higher correlation with low flows calculated by $SWAMP_{OM}$, compared to high flows. On the other hand, higher historical water levels are more correlated with higher water levels computed by $SWAMP_{OM}$, compared to the lower water levels.

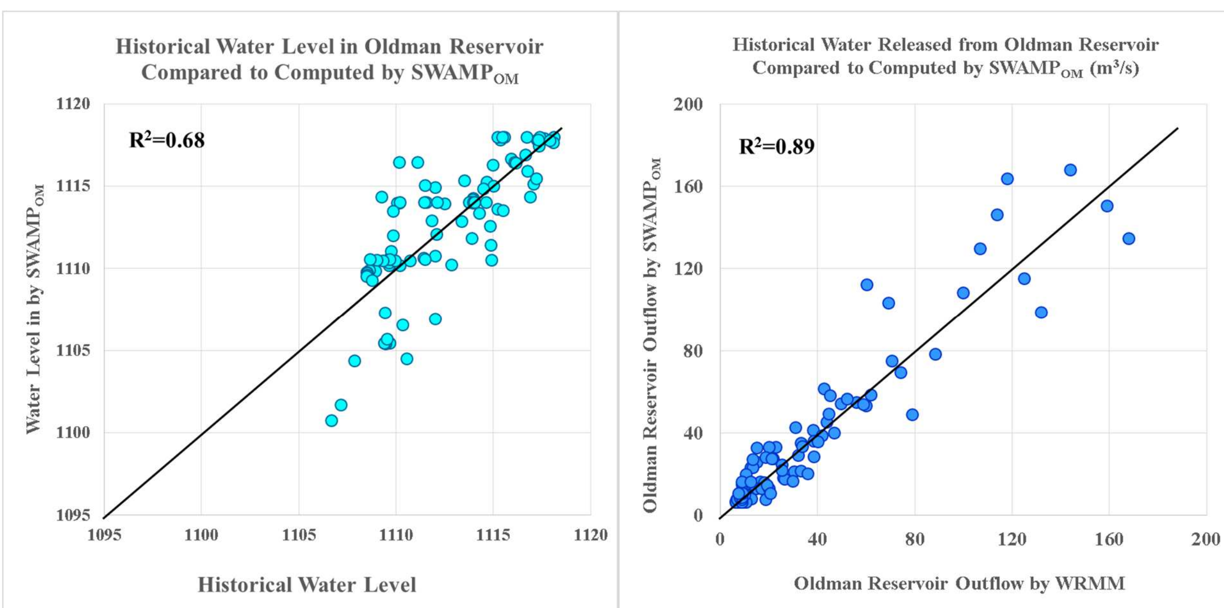

Figure 4.15: Water level and water released from the reservoir compared to the monthly historical data

There are also three consecutive reservoirs, located in the north of the OMRB, which have been modelled by WRMM, as well as $SWAMP_{OM}$ (Figure 4.16). They receive water from the Willow Creek River and all of them have two operating zones, corresponding to the physical maximum and minimum levels. The first reservoir is the Chain Lake and has the maximum storage capacity of about 57.24 MCM. The second reservoir is the Divpond for which maximum storage level is 10.65 MCM. The largest reservoir in the north of the basin is Pine Coulee Reservoir with a maximum storage capacity of 66.61 MCM.

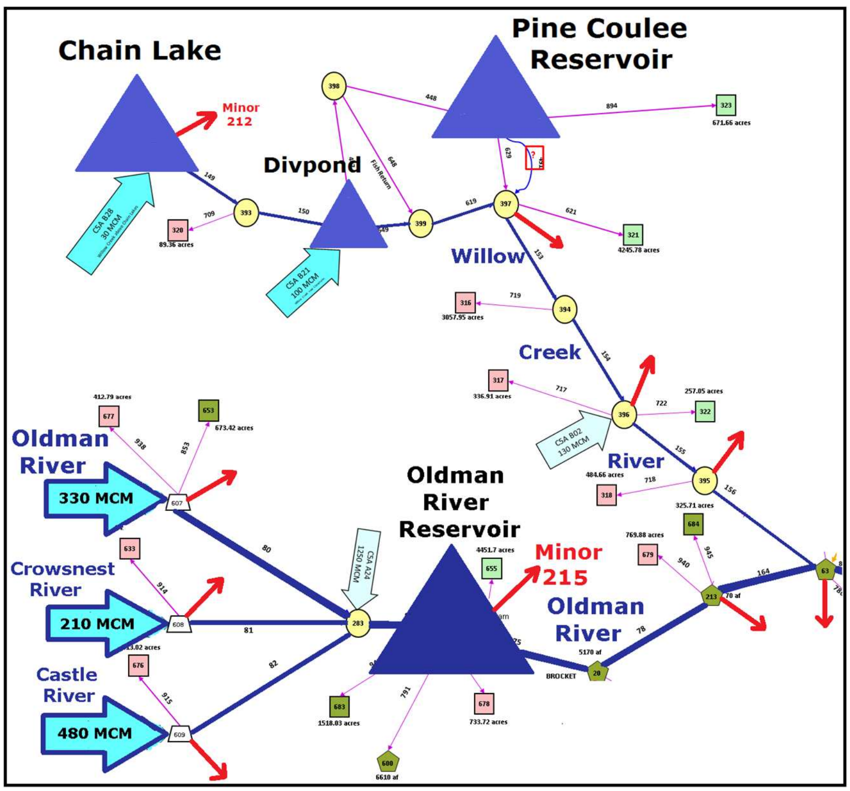

Figure 4.16: Schematic map of the Chain Lake, Divpond and Pine Coulee Reservoirs' location

Figure 4.17 shows three scatter plots of reservoir water levels modeled by WRMM and $SWAMP_{OM}$. As can be seen, $SWAMP_{OM}$'s results for the Chain Lake's water level are quite well matched with WRMM's results and R^2 is 0.99. For the Divpond, R^2 decreased to 0.92. Pine Coulee

Reservoir water level simulated by WRMM and $SWAMP_{OM}$ has the lowest R^2 (0.80), and $SWAMP_{OM}$ stored less water in the reservoir for higher water levels compared to WRMM. However, for lower water levels $SWAMP_{OM}$ stored more water.

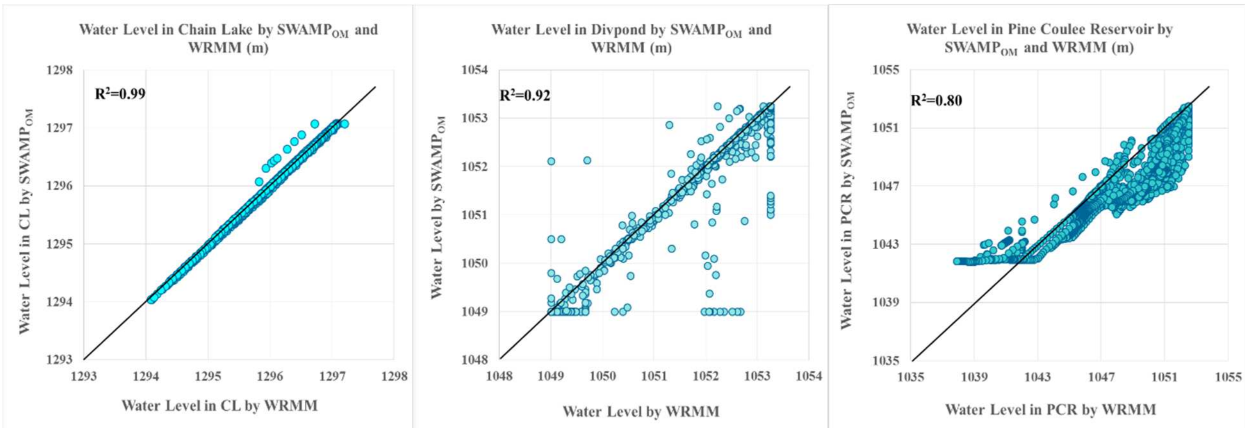

Figure 4.17: Scatter plots of Chain Lake, Divpond and Pine Coulee reservoirs water level between $SWAMP_{OM}$ and WRMM's results

4. 2. Performance of Dynamic Irrigation Demand Sub-model

The water allocation model delivers water to irrigation fields based on how much water they require (irrigation demand). Irrigation demand is a function of climate variables, soil moisture, and crop types. Therefore, it changes under different climate conditions, and differs in each irrigation district in the Oldman River Basin. As a result of growing uncertainty in climatic variables and water supply in the basin, it is important to have a reasonable estimation of irrigation districts' demand, which has therefore been calculated by a dynamic irrigation demand sub-model. In the Lethbridge Northern ID, as the largest irrigation district in the basin, eight different crops (barley, wheat, alfalfa, canola, flax, corn, sugar beet, and potato) are planted. In the St. Mary and Taber IDs, beans are planted besides the crops sowed in the NLID. The Ross Creek ID, which includes only two irrigation fields, produces only two crops, alfalfa and barley. There is no documentation about the crops planted in the private ID; hence it was assumed that two crops, alfalfa and wheat, which are the most common in the OMRB, are planted there.

Figure 4.18 shows annual dynamic irrigation demands of the Lethbridge Northern ID calculated by $SWAMP_{OM}$, and annual fixed demands obtained from WRMM. On average, $SWAMP_{OM}$ has calculated the irrigation demands (IDs) of LNID, 4.7% less than WRMM on the annual timescale. (Table 4.1). This difference has increased in weekly timescale and reached 12.5%. For Ross Creek ID the difference between the irrigation demands calculated by $SWAMP_{OM}$ and obtained from WRMM, is 5.6% and irrigation demands calculated by $SWAMP_{OM}$ is less than those of WRMM. On the other hand, for St. Mary, Taber, and Private IDs, demands calculated by $SWAMP_{OM}$ are more than WRMM (Table 4.1).

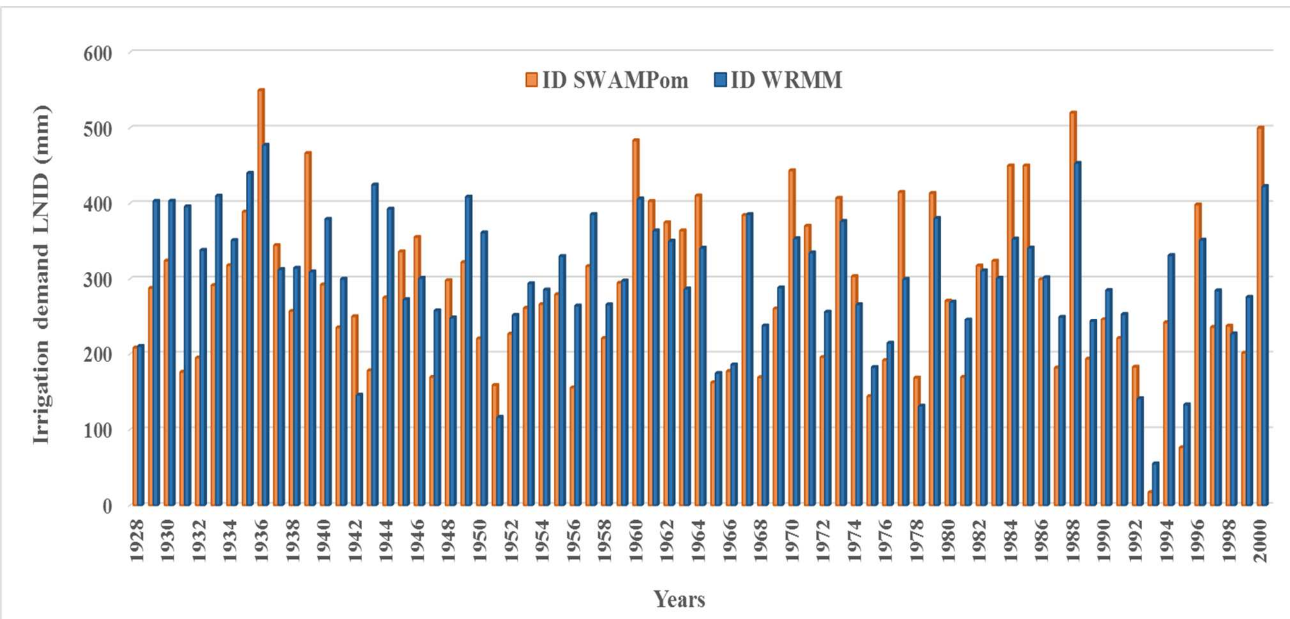

Figure 4.18: Irrigation Demands calculated by $SWAMP_{OM}$ and Obtained from WRMM for Lethbridge Northern Irrigation Districts

Table 4.1: Averaged Percentage Error between Irrigation Demands calculated by $SWAMP_{OM}$ and Obtained from WRMM for Each Irrigation District

Irrigation Districts	Weekly	Annual
Lethbridge Northern ID	-12.45	-4.67
St. Mary and Taber ID	0.63	1.66
Ross Creek ID	-10.34	-5.6
Private ID	14.02	0.44

Figure 4.19 shows weekly irrigation demand of each irrigation district calculated by $SWAMP_{OM}$ from 1996 to 2001 (It is difficult to show the demand for all simulation years in one graph. Therefore, the estimated demand from 1928 to 1995 is plotted in a separate graph and included in Appendix B). Since the crops planted in the St. Mary and Taber IDs are identical and both have the same elevation and climatic data (there is just one meteorological station close to these two irrigation districts, and data from this station were used in the calculation of irrigation demand), the estimated irrigation demand for both of them is equal.

NLID, PID, SMRID, and TID's demands follow the same trend and they need irrigation from first week of May. Their maximum demands occur in late June or early July, and in very warm years their demands reach more than 60 mm per week. RCID should be irrigated one week after other IDs. The peak value of its demand is about 54 mm in the very dry years and about 10 mm less than the other IDs' maximum demand.

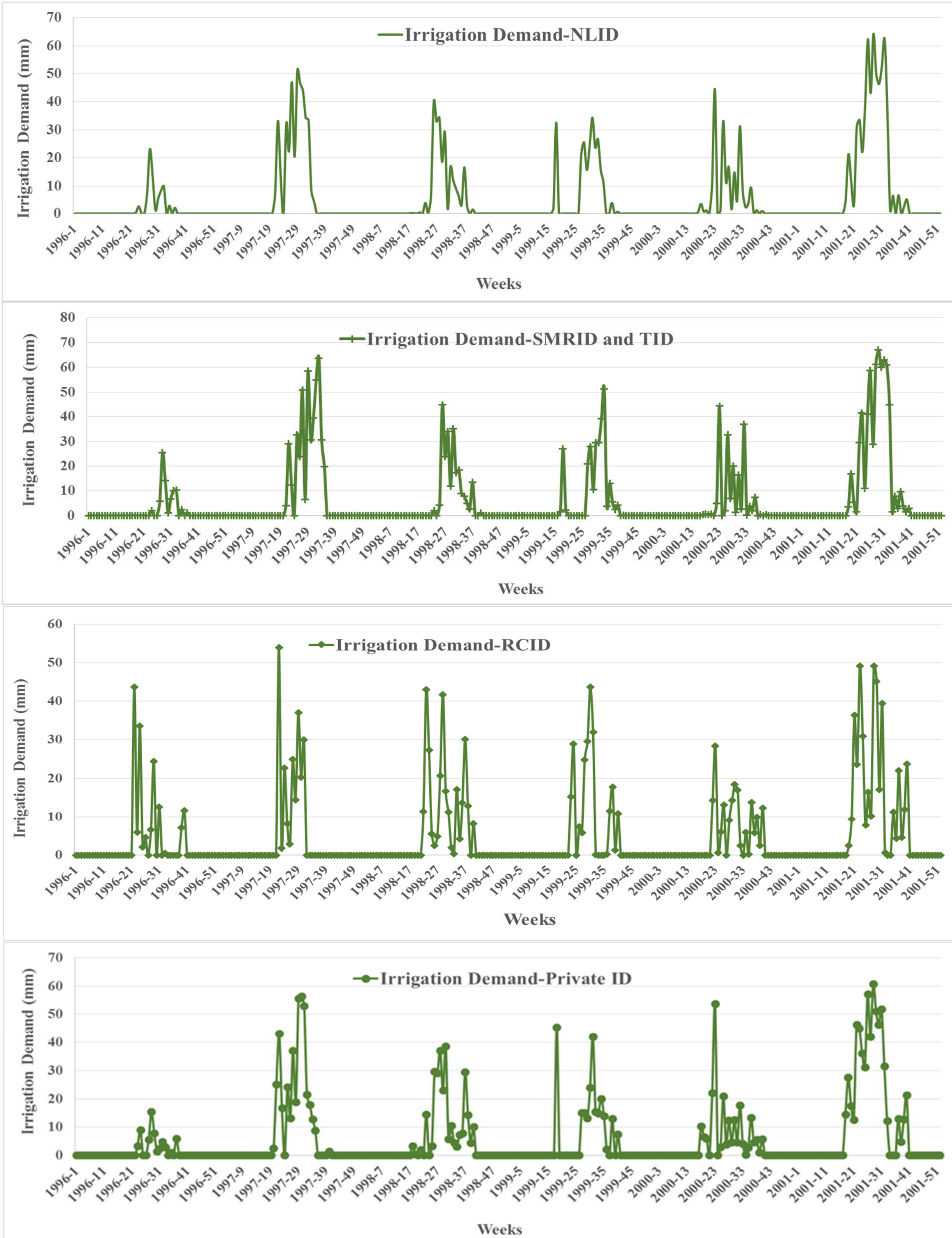

Figure 4.19: Weekly irrigation demand of NLID, SMRID, TID, RCID, and PID from 1996 to 2001

4. 3. Performance of Instream Flow Need Sub-Model

Instream flow need (IFN) is the amount of water required to flow in rivers to protect aquatic ecosystems. Weekly IFNs were calculated for the six sections of the Oldman River using the Alberta Desktop Method in this study. Figure 4.20 shows Weekly IFNs for each section of the Oldman River from 1996 to 2001 calculated by $SWAMP_{OM}$ and WRMM which uses the fish rule curve method. IFNs calculated by $SWAMP_{OM}$ are 37% higher than those obtained from WRMM.

IFNs of all sections have one peak in late June in general. However, in 2000 an extra peak has been calculated for IFN in late November by $SWAMP_{OM}$, due to an increase in the natural flows of the basin. The peak IFN calculated by $SWAMP_{OM}$ is about 85 m^3/s (it is slightly more than this amount in wet years), while it is approximately 22 m^3/s when obtaining from WRMM. The peak IFN of section 3 calculated by $SWAMP_{OM}$ remains equal to 82 m^3/s within the 74 year period; but it has some variations from year to year for other sections, and rise up to two times in the very wet years, like 1996 (figure 4.20). The peak IFN of sections 1, 2, and 4 are equal to approximately 84 m^3/s, and this number increases to 92 and 97 m^3/s for section 5 and 6, respectively.

The minimum IFN computed by $SWAMP_{OM}$ for sections 1, 2, 3, and 4 is about 5.5 m^3/s. But, this number increases to 9 and 11.5 m^3/s for sections 5 and 6, respectively. Sections 5 and 6 receive water from St. Mary and Belly River, besides the Oldman River. Therefore, IFNs of these sections are higher than IFNs of other sections. On the other hand, the minimum IFN obtaind from WRMM is approximately 6 m^3/s for sections 1, 2, 3, 4 and 5, and rises to 11.5 m^3/s for sections 5.

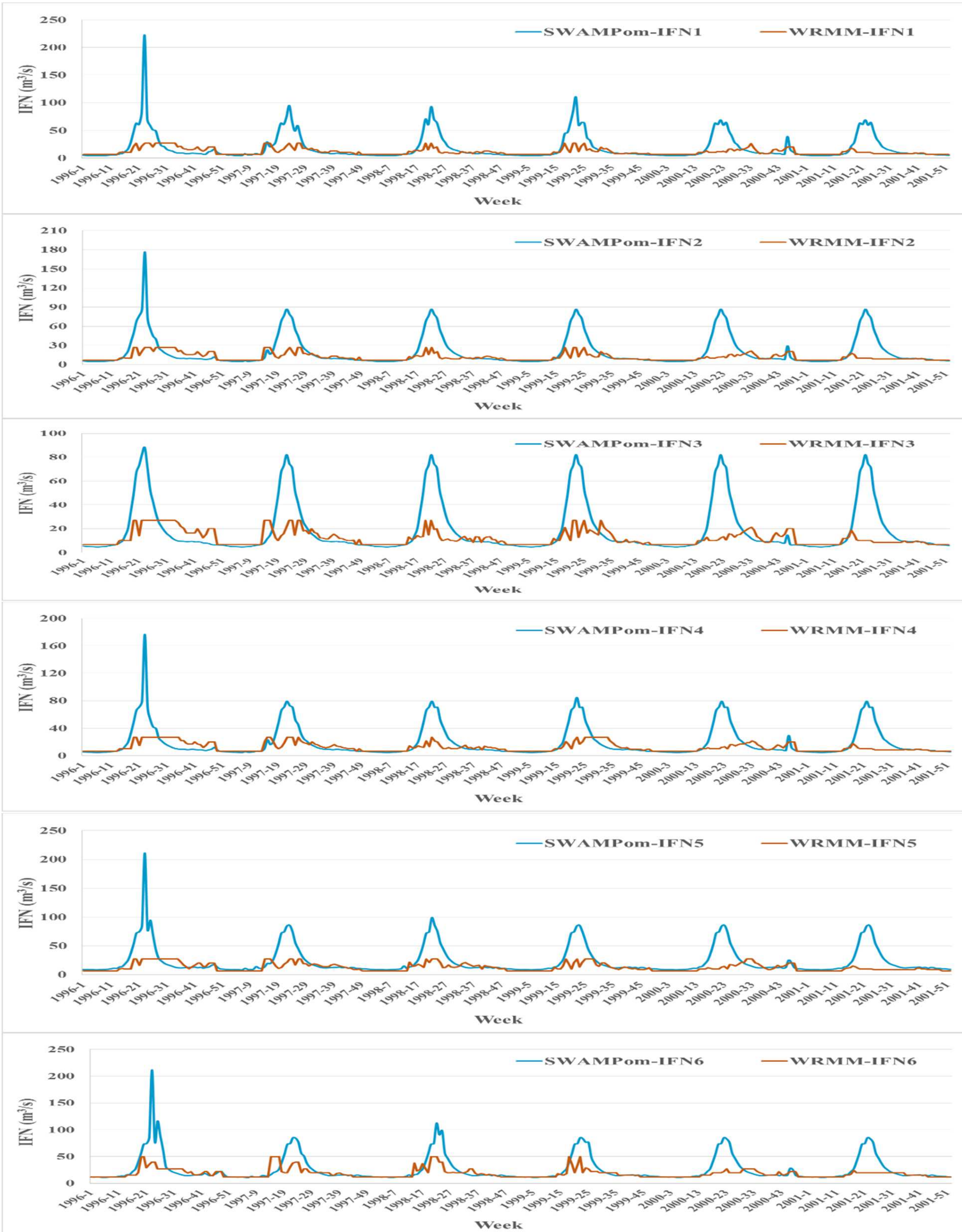

Figure 4.20: Weekly IFN of the six sections of the Oldman River from 1996 to 2001 calculated by $SWAMP_{OM}$ and WRMM

Figure 4.21 depicts the amount of water allocated to IFN for the section 1 of the Oldman River by $SWAMP_{OM}$ and WRMM from 1996 to 2001. Since the IFN calculated by $SWAMP_{OM}$ is more than that obtained from WRMM, $SWAMP_{OM}$ allocates more water to IFN than WRMM does. However, it cannot meet all IFNs under current hydrological conditions. Figure 4.22 shows the number of weeks that WRMM and $SWAMP_{OM}$, could not have satisfied the IFN in whole time period from 1928 to 2000.

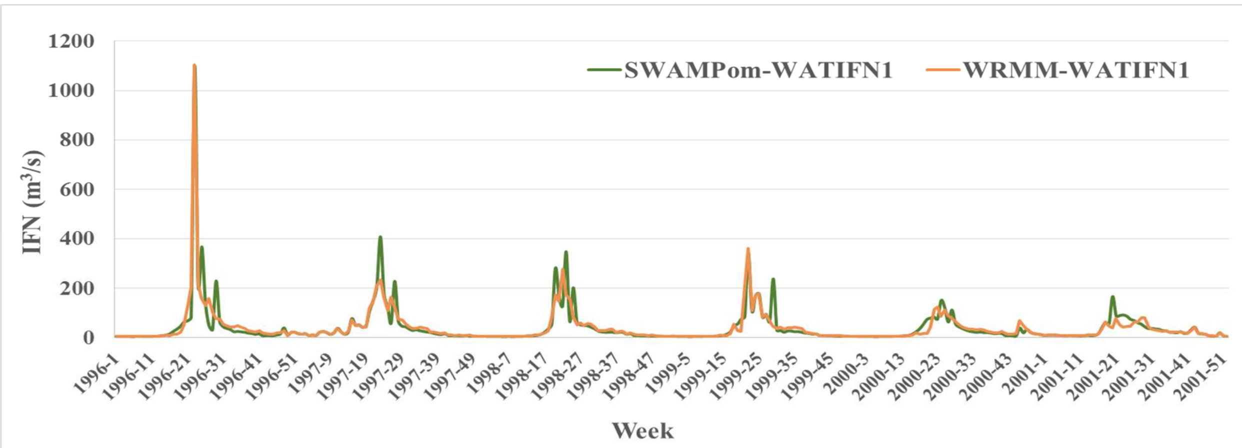

Figure 4.21: Amount of water allocated to IFN for the section 1 of the Oldman River by $SWAMP_{OM}$ and WRMM from 1996 to 2001

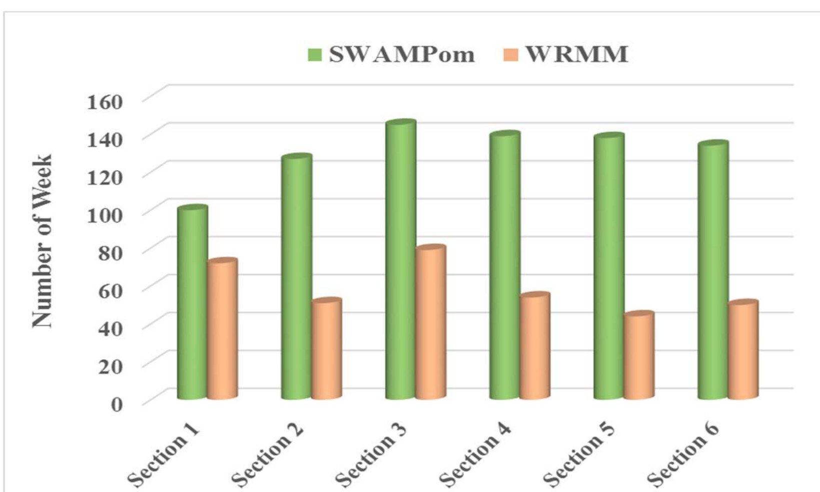

Figure 4.22: Number of weeks that WRMM and $SWAMP_{OM}$ could not meet IFN from 1928 to 2000

4. 4. Performance of Economic Evaluation Sub-Model

Water-related economic benefit in the OMRB is mostly earned by crop production and hydropower electricity generation. Figure 4.23 depicts annual economic benefit, calculated by the economic evaluation sub-model in the basin. The maximum monetary gain is 328.5 M$ in 1993, followed by 260 and 252 M$ in 1978 and 1942, respectively. In these three years, annual water supply is up to 90% more than the mean annual water supply of the basin. On the contrary, 1988, 1985, and 2001 are the years when the minimum financial profit is made and it is only 82.8 M$ in 1988. In that year, the average annual temperature is 8.31 ^oC, 2.5 ^oC higher than the mean annual temperature of the basin. In addition, annual water supply is half of the mean annual water supply of the basin.

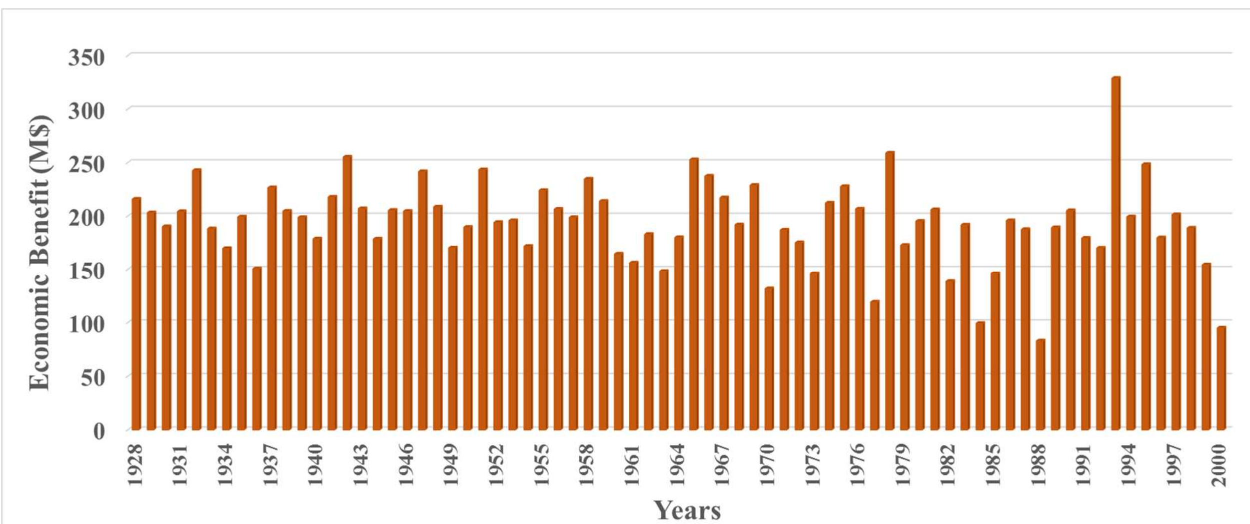

Figure 4.23: Annual economic benefit in the OMRB from 1928 to 2001

As can be seen in figure 4.23, a decrease in calculated annual economic benefit can be followed in the 70's and 80's, and profits earned in the 30's, 40's, and 50's are slightly more than those in the remaining decades. While figure 4.24 shows that mean annual streamflow has been marginally increasing in this period, figure 4.25 depicts that mean annual temperature has been rising less than 1 °C, and has caused an escalation in actual evapotranspiration and remarkable growth in the crop water demands (figure 4.26). Therefore, ETa/ET_o, the main factor in calculation of crop productivity (Refer to chapter 3, equation (3.6)), has increased (Figure 4.27); hence, a marginally negative trend can be followed in the economic benefit from 1928-2001.

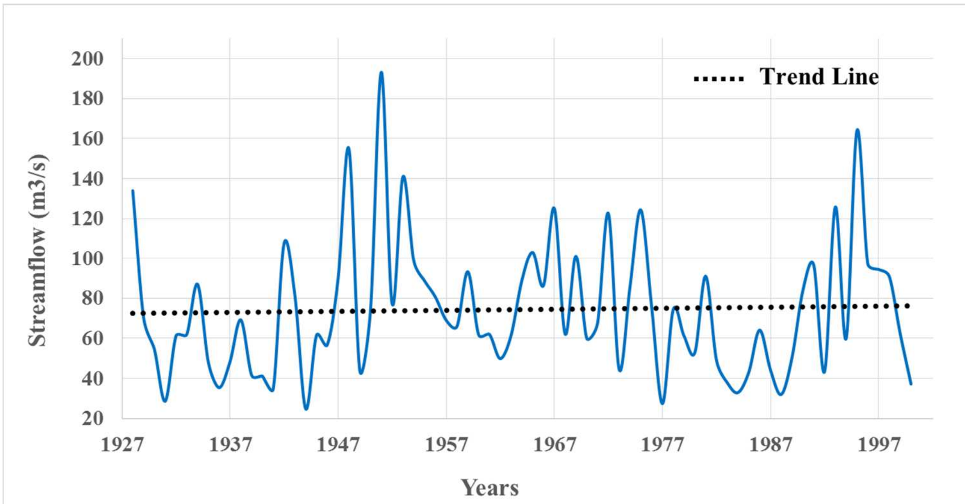

Figure 4.24: Average annual streamflow (m^3/s) from 1928 to 2000

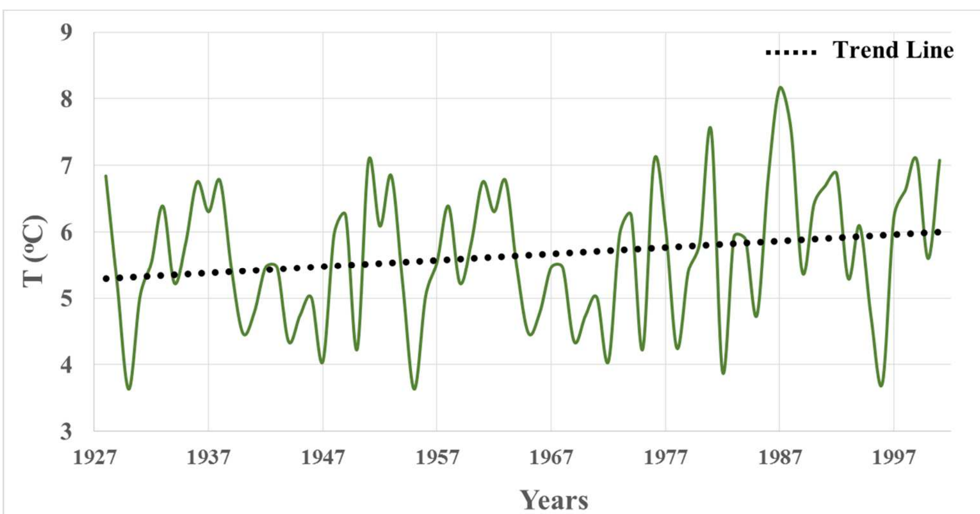

Figure 4.25: Average annual temperature (°C) from 1928 to 2000

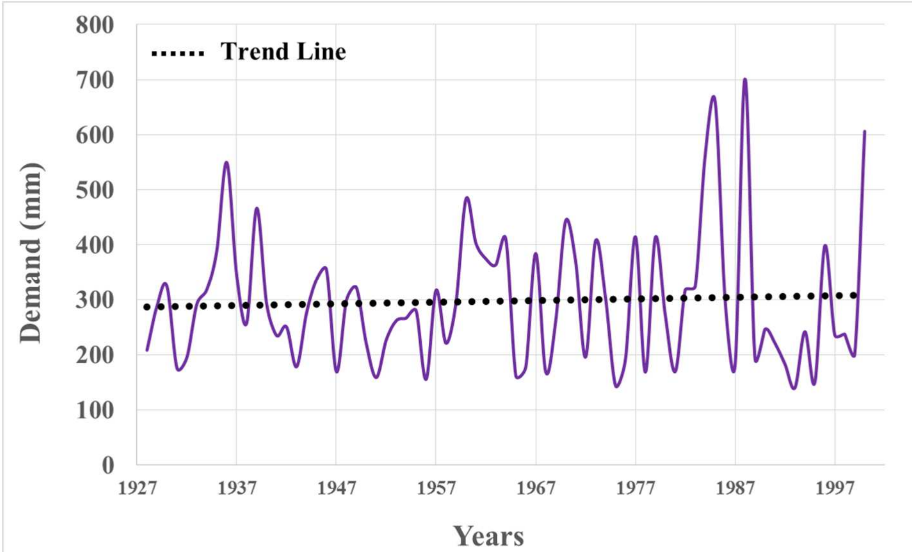

Figure 4.26: Crop water demands from 1928 to 2001

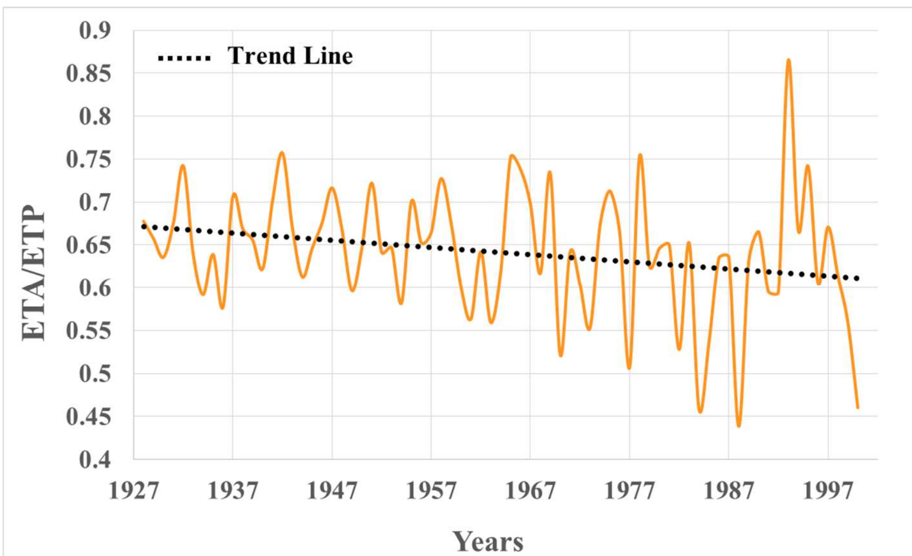

Figure 4.27: Annual Et_a/ET_0 from 1928 to 2001

4. 5. Effect of Simultaneously Changing Oldman Flow and the IFN Percent of Natural Flow Component on Water Allocated to IFN and the Basin's Economy

As some IPCC climate change scenarios show, the Oldman River streamflow can change -18% to +4% in future (AMEC, 2009). This change definitely will affect the amount of water allocated to each user, and hence the basin's economy and ecosystem. Besides changing the river flow, there is a concern in water allocation plans to meet ecosystem demands. In this section, the influence of changing simultaneously instream flow need (IFN) and Oldman Flow on the economic viability and the water allocated to IFN is examined. The Oldman flow was changed with the ratios of 0.8, 0.9, 1.1, and 1.15, and the IFN percent of natural flow component (Refer to table 3.2, section 3. 4. 3), also was changed with the ratios of 0.8, 1, and 1.2. $SWAMP_{OM}$ was simulated under 12 different scenarios for 74 years, from 1928 to 2001. Figure 4.28 indicates the water allocated to IFN under six scenarios, from 1996 to 2001, as an example. In this graph, the phrase of *"WAIFN (1.15, 0.8)"* specifies the graph showing the water allocation to IFN under the scenario of change in the Oldman flow with the ratio of 1.15 and change in the IFN percent of the natural flow component with the ratio of 0.8.

While changing the Oldman flow dramatically affects the amount of water allocated to IFN, changing the IFN percent of natural flow component does not have a significant influence on it (figure 4-28). When the ratio of changing the Oldman flow increases from 0.8 to 1.15, the water allocation to IFN grows by double. However, escalating the ratio of the IFN percent of natural flow component from 0.8 to 1.2 increases it slightly. In most weeks the multiplication of the IFN percent of natural flow component by the Oldman flow (Method which is used to calculate IFN in Alberta Desktop Method; section 3. 4. 3) is less than the base flow and the base flow is applied as IFN. Therefore, changing the IFN percent does not have a large influence on the IFN and IFN remains approximately constant. Hence, the water allocated to IFN does not change very much.

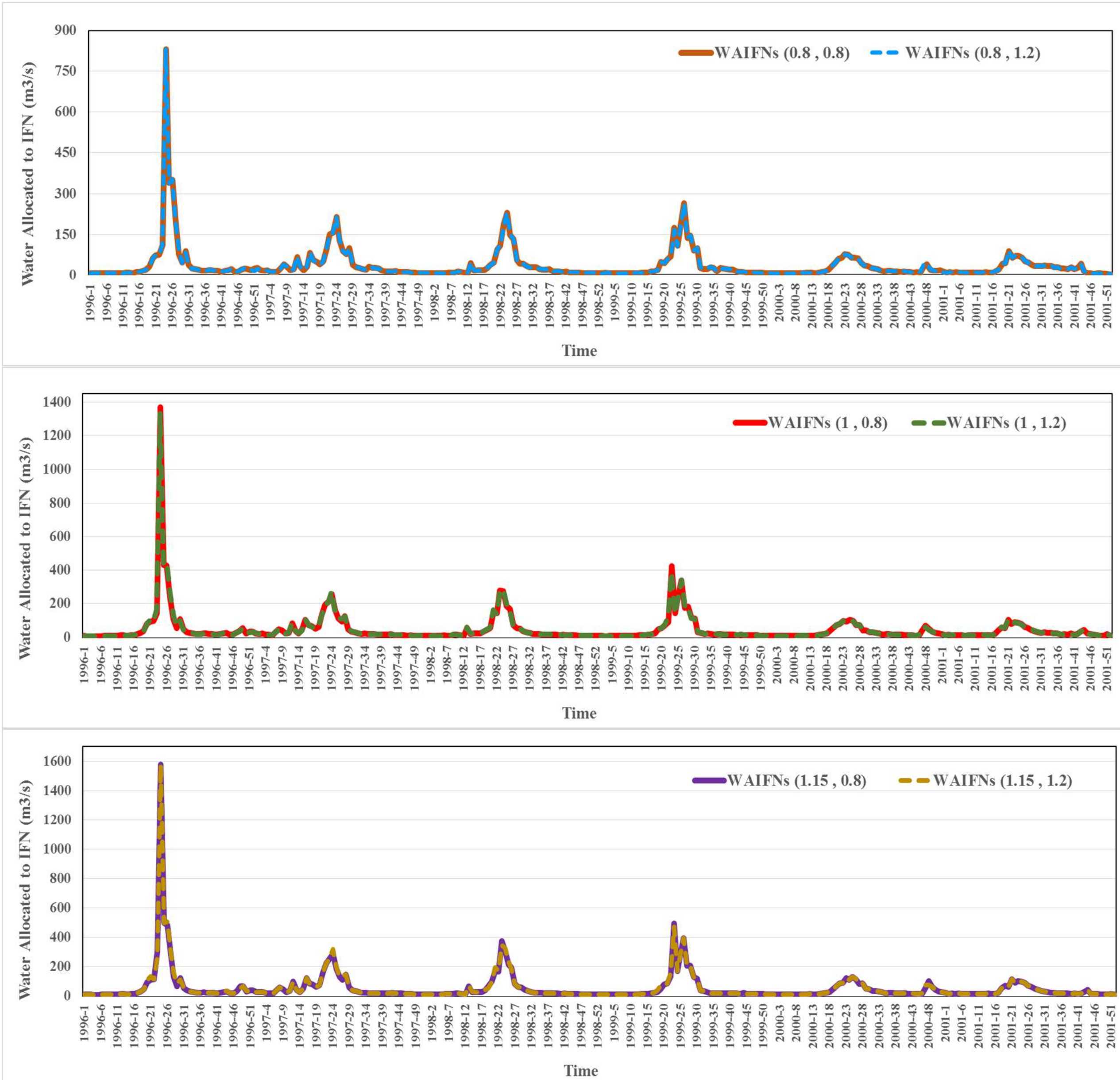

Figure 4.28: Water allocated to IFN under 6 scenarios WAIFN (0.8, 0.8), WAIFN (0.8, 1.2), WAIFN (1, 0.8), WAIFN (1, 1.2), WAIFN (1.15, 0.8), WAIFN (1.15, 1.2), from 1996 to 2001

$SWAMP_{OM}$ could usually satisfy IFN and the water allocated to IFN is usually more than the demand. Figure 4-29 depicts the number of the week when the model could not meet the IFN in 74 years under 12 scenarios. In this figure “S (0.9, 1.2)” specifies the scenario of change in the Oldman flow with the ratio of 0.9 and change in the IFN percent of the natural flow component with the ratio of 1.2, for instance. If the Oldman flow increases, the IFN will also grow; but, the number of weeks that IFN has not been met will decrease (figure 4-29), because there is enough water to allocate to IFN. On the other hand, the increase of the IFN percent of the natural flow component will result in a small growth of IFN, thus, it has a small effect on the number of weeks that IFN was not met. However, it has increased slightly (Figure 4-29).

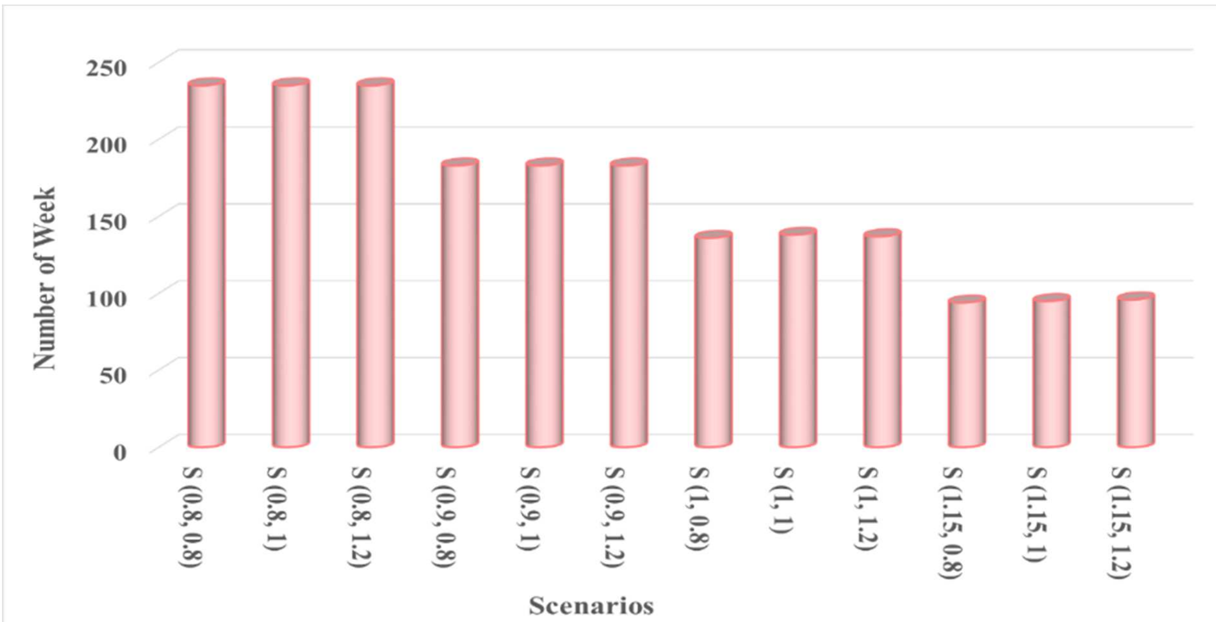

Figure 4.29: The number of the week that $SWAMP_{OM}$ could not meet the IFN in 74 years under 12 scenarios

Changing the IFN percent of natural flow component affects slightly the basin's economy, like its effect on the water allocated to IFN. However, the variation of the Oldman flow has more influence on the financial gain and increases it, particularly in the dry years, such as 1985 and 1989 (Figure 4-30).

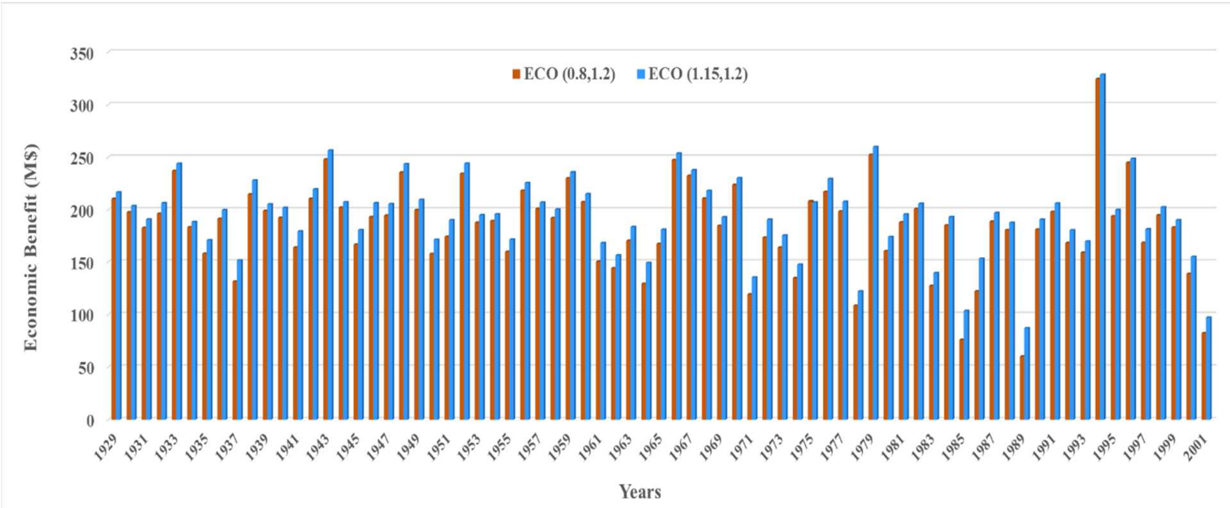

Figure 4.30: Effect of changing the Oldman flow and IFN percent of the natural flow component on the economic benefit under two scenarios of S (0.8, 1.2) and S (1.15, 1.2)

4. 6. Pareto Front, a Method to Study Environmental and Economic Goals under Flood Protection Condition

In a basin that is highly regulated by reservoirs, like the Oldman River Basin, water reservoir management is essential to balance economic and environmental protection objectives while avoiding floods. Due to the complexity of reservoir management (Simonovic, 1987), optimization approaches are typically applied to solve operational reservoir problems (Liu et al., 2011). In the optimization problem, which involves multiple conflicting objectives, the Pareto front method is very practical, if there is no single, feasible solution to optimize all objectives together (Augusto et al., 2012). This method can illustrate the trade-off between the different objectives and thus help to make the best decision based on the importance of each objective and the decision maker's preference among the objectives. In this study, this approach was applied to quantify the trade-offs between optimal basin economic performance, water allocation to IFN and flood protection, in order to find the Pareto-optimal sets of operating zones of the Oldman River

Reservoir, which is the largest multi-task reservoir in the basin.

The Oldman River Reservoir currently has four important operating zones to allocate water to downstream demands (Figure 4.31). It may not store more than the maximum storage zone and less than the minimum storage zone, and they represent the reservoir's extreme physical constraints. Hence, the Pareto-optimal sets of two other operating zones, flood control and middle operating zones, will be identified by the Pareto approach here.

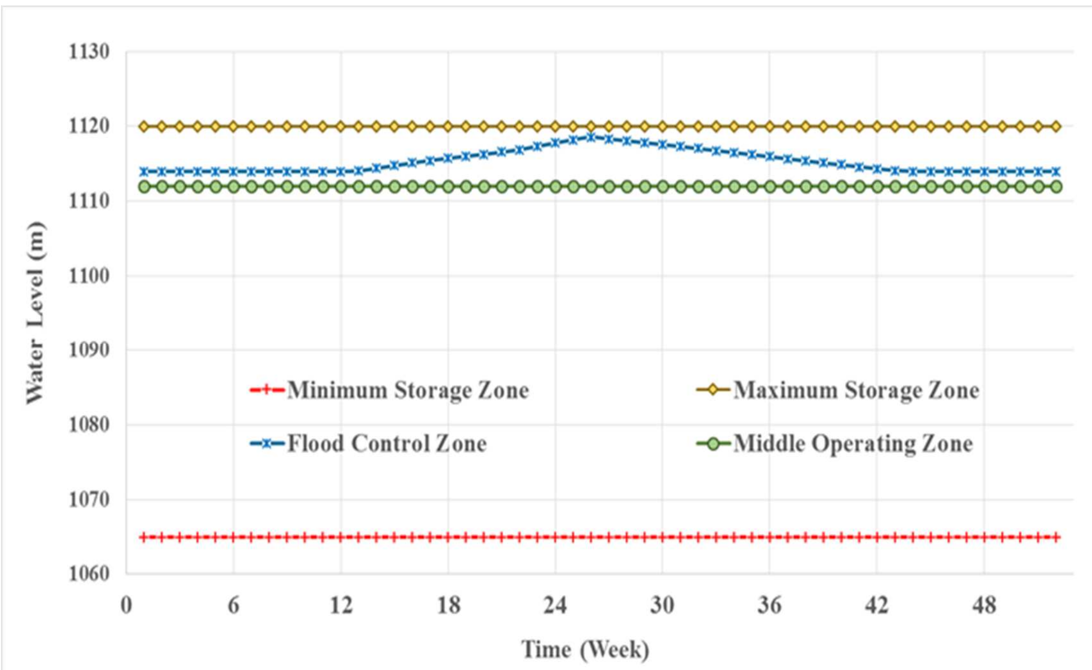

Figure 4.31: The Oldman River Reservoir operating zones

4. 6. 1. Pareto Front Approach

To present an optimal set of two operating zones for the Oldman River Reservoir, a multi-objective approach, is used to maximize the basin's economy, and the water allocated to instream flow needs, and produce flood security. To solve such multi-dimensional optimization problem, which does not have one optimal solution to meet all objective functions (OFs) together, the Pareto front approach is very useful. The Pareto front is a framework to evaluate a set of decision variables with multi-dimensional outputs assuming that improvement in one dimension will result in being worsen in another (Legriel et al., 2010). It represents trade-offs between objective functions, which is very practical in decision making process. To find optimal Oldman Reservoir operating zones, the Pareto approach requires to optimize three objective functions, economic, environmental (IFN), and flood OFs, simultaneously. Since both the amount of floodwater and flood frequency are very important, two objective functions were defined to protect the basin from flooding. Equations 4.1 to 4.4 represent objective functions which have been assigned:

$$Economic\ OF = \min\left(\sum_{i=1}^{74}\left(\frac{(Max\ EB - EB_i)}{Max\ EB_i}\right)\right)/74 \quad (4.1)$$

$$Environmental\ OF = \min\sum_{i=1}^{74}\sum_{j=1}^{52}\left(\frac{(IFN\ OMR_{i,j} - WAIFN\ OMR_{i,j})}{IFN\ OMR_{i,j}}\right)/(74\times 52) \quad (4.2)$$

$$Flood\ OF(1) = \min\sum_{i=1}^{74}\sum_{j=1}^{52}\left(\frac{(Outflow_{i,j} - FT)}{FT}\right)/(74\times 52) \quad (4.3)$$

$$Flood\ OF(2) = Flood\ Frequency = \min\left(\sum_{i=1}^{74}\sum_{j=1}^{52} Number\ of\ Floods\right) \quad (4.4)$$

where i and j are the year and week index respectively, *Max EB* is the maximum economic benefit which can be earned in a year, EB_i is the actual economic benefit in year i, $IFN\ OMR_{i,j}$ is the average weekly instream flow need of the Oldman River, $WAIFN\ OMR_{i,j}$ is the average weekly water allocated to IFN, $Outflow_{i,j}$ is the average weekly water released from the Oldman Reservoir, and *FT* is flood threshold.

The economic objective function aims to minimize the difference between the maximum and actual economic benefit. To calculate *Max EB*, it is assumed that crop's annual yield would be maximum. Then, economic benefit for each crop is calculated using equation 3.10 and 3.11 Maximum hydropower generation in the basin is 32 MWh. Multiplication of this maximum generation by revenue and cost for one year results in maximum economic benefit from this sector. The summation of results for all crops and hydropower generation would bring about *Max EB*. Minimization of difference between the water allocated to the ecosystem and IFN is the objective followed by the environmental objective function. While flood objective 1 tries to minimize the downstream floodwater, flood objective 2 decreases the flood frequency. For both flood objective functions, the median of annual historical peak flows is defined as a flood threshold (Bayliss and Jones, 1993), so that the weekly peak flow of each year is extracted and 50% percentile of these peak flows is specified as flood threshold which is 263 m^3/s.

To reach the optimal sets of solutions, first 100,000 different sets of two operating zones (flood control zone and middle operating zone) are generated using the Monte Carlo approach. Second, $SWAMP_{OM}$ is simulated under each set and weekly water released from the reservoir, weekly water allocation to the IFNs and basin's economic benefit are calculated. Afterwards, objective functions are computed for each set of operating zones, and a four dimensional Pareto solution with four axes representing the four OFs is obtained for the OMRB. To clearly illustrate this multi-dimensional solution, it is visualized in five two-dimensional surfaces. The lower border of these surfaces represents the trade-offs between optimal sets of operating zones, called a Pareto front.

4. 6. 2. Optimal Sets of Operating Zones using Pareto Front Approach

Since there are four objective functions in this study, the four dimensional Pareto solution has been illustrated in five Pareto surfaces (figures 4.32, 4.35, 4.38, and 4.41). Figure 4.32 shows the Pareto surface (PS) and Pareto front (PF) (orange line) of economy and IFN objective function (Called PSEI and PFEI later). Each point on the PSEI is the outcome of two economy and IFN objectives under simulation of a specific set of two operating zones. The purple point on the PFEI indicates a set of operating zones with maximum economic benefit, and the green point shows a set with maximum water allocated to IFN.

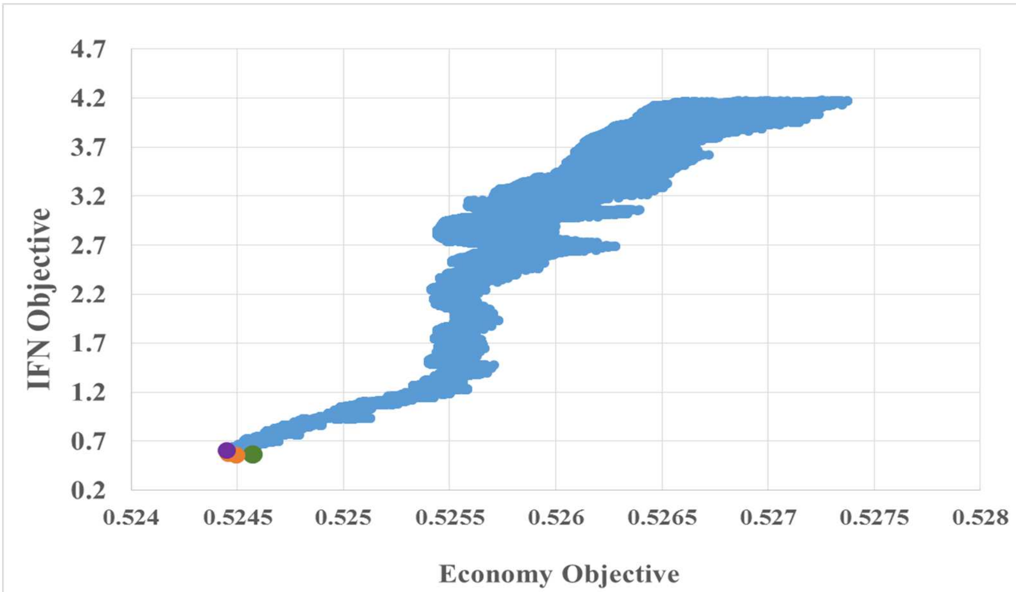

Figure 4.32: Pareto surface and Pareto front of economy and IFN objectives

Figure 4.33a shows the flood control zones of each point on the PFEI, and figure 4.33b depicts corresponding middle operating zones. The flood control zone, indicating maximum economic benefit (dark brown curve in figure 4.33a) begins from the level of 1117.04 m (named "initial level" later), and in 14th week starts (starting week) to increase gradually and reaches the maximum level of 1119.5 m in 24th week. Then, it decreases and in week 44 returns to the initial level of 1117.04 m. As the initial level increases, more water is allocated to IFN and economic benefit decreases, so that flood control zones with lower initial level result in more economic benefit, while flood control zones with higher initial level bring about more water allocated to IFN. The dark green curve in figure 4.33a represents the flood control zone with maximum water allocated to IFN. It increases in week 11 and its peak occurs in week 23. It touches the initial level of 1117.32 m in week 44 again. As can be seen in figure 4-34a, the flood control zones resulting in more water allocation to IFN, start to increase two/three weeks earlier than the zones resulting in more economic gains. The middle operating zones, which are meeting the economy objective, have lower levels than the middle operating zones which are satisfying the IFN objective function.

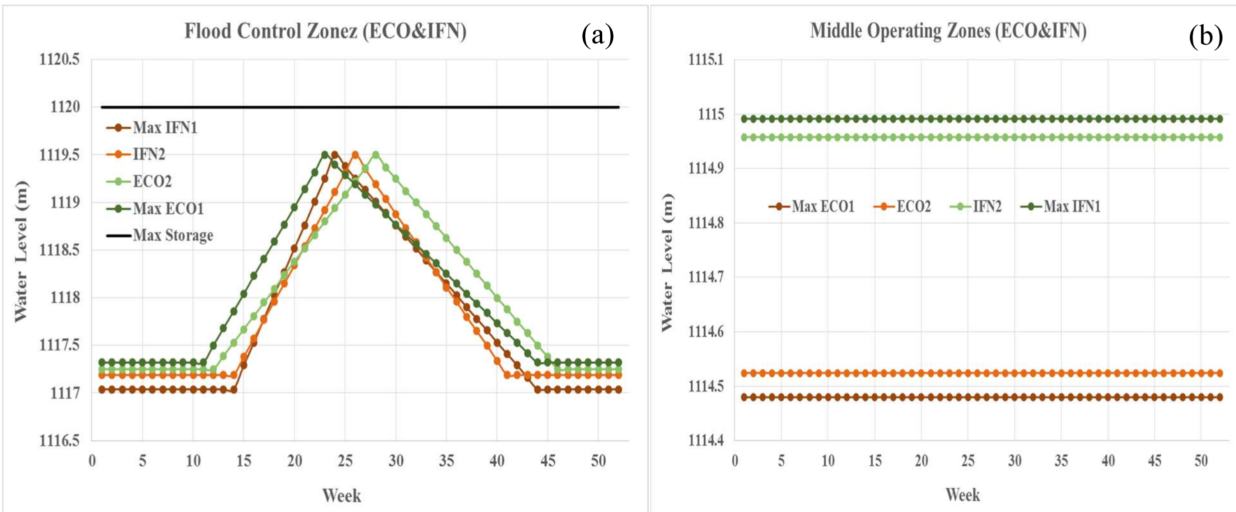

Figure 4.33: Flood control zones (a) and middle operating zones (b) of each point on the PFEI

Figure 4-34 shows the operating zones causing the maximum economic benefit (orange curves; according to the purple point on the PFEI) and the maximum water allocated to IFN (green curves; according to the green point on the PFEI).

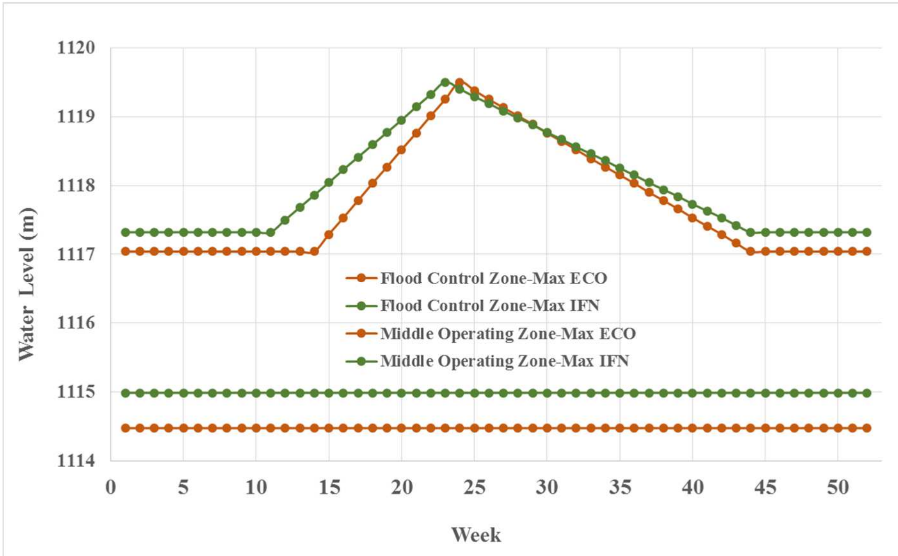

Figure 4.34: Operating zones causing the maximum economic benefit (orange curves) and the maximum water allocated to IFN (green curves) on the PFEI

The Pareto surface and Pareto front (orange line) of economy and flood objective function 1 (Called PSEF1 and PFEF1 later) which aim to minimize downstream floodwater, have been depicted in figure 4.35.

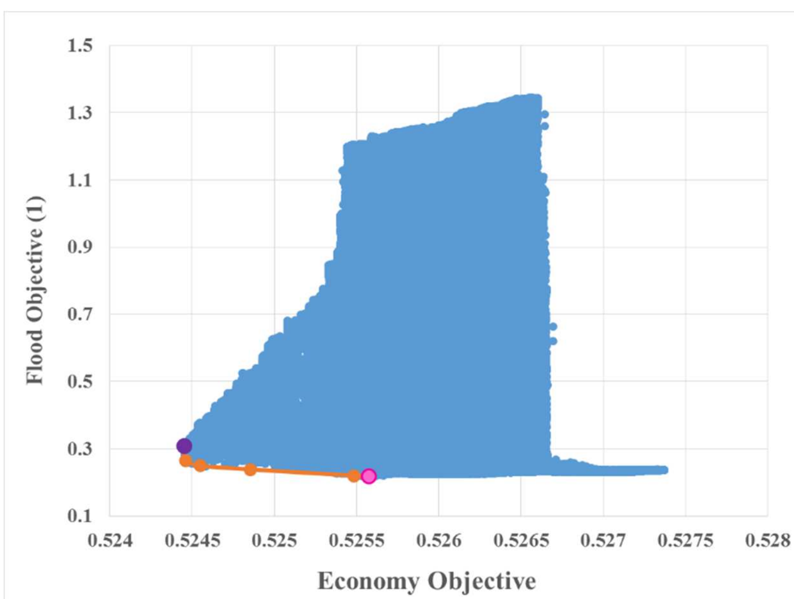

Figure 4.35: PSEF1 and PFEF1

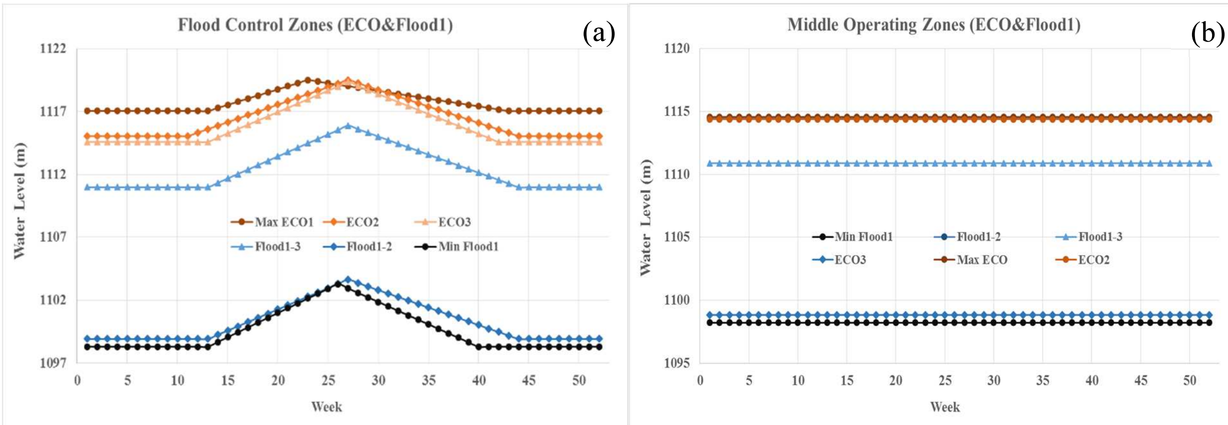

Figure 4.36: Flood control zones (a) and middle operating zones (b) of each point on the PFEF1

The flood control zones and middle operating zones of each point on the PFEF1 have been shown in figures 4.36a and 4.37b, separately. When initial level is low in the flood control zone, the reservoir has more capacity to store the floodwater. Therefore, as can be seen in figure 4.36a, the initial level of flood control zone indicating minimum floodwater (darkest blue curve) is much lower than that representing maximum economic benefit (darkest brown curve). It is 1098.94 m for flood control zone with minimum floodwater, but 1117.04 m for flood control zone with maximum economic benefit. Both flood control zones resulting in more economic benefit and less flooding start to increase in 13th week. Like the initial water level, the peak value for the economic flood control zones are much higher than this value for the zones resulting in more flood security. Like the middle operating zones of PFEI, there is a strong relationship between the optimal middle operating zones stemmed from the two economic and flood 1 objective functions, so that the middle operating zones resulting in more financial gain, have higher levels than those having less floodwater, in general. Figure 4-37 shows the operating zones resulting in maximum economic benefit (orange curves; according to the purple point on the PFEF1) and the maximum flood security (blue curves; according to the pink point on the PFEF1).

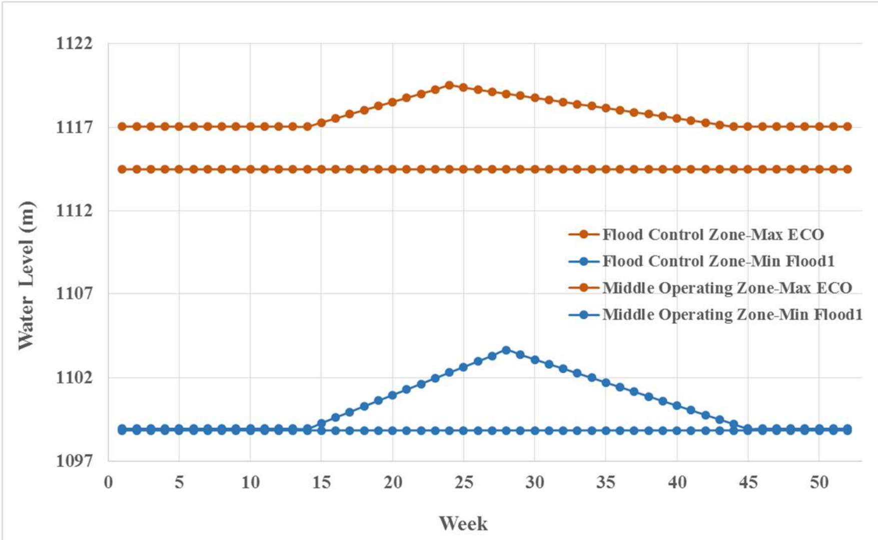

Figure 4.37: Operating zones causing the maximum economic benefit (orange curves) and the minimum floodwater (blue curves) on the PFEF1

If the economic objective is replaced by the IFN objective in figure 4.37, the Pareto curves are changed to figure 4.38. In this figure blue points show the Pareto surface (PSIF1) and the orange line indicates the Pareto front (PFIF1). Pink and green points represent two sets of operating zones with minimum floodwater and maximum water allocated to IFN, respectively.

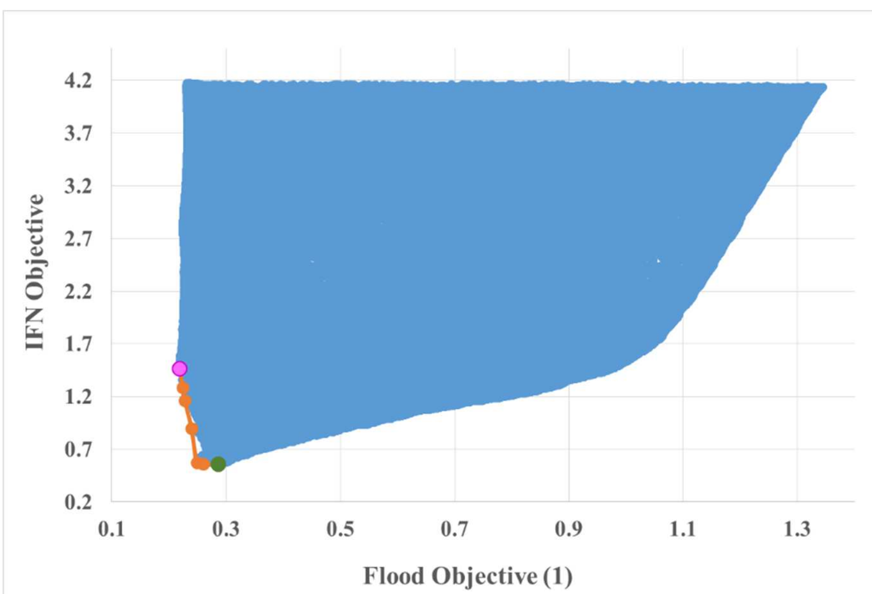

Figure 4.38: PSIF1 and PFIF1

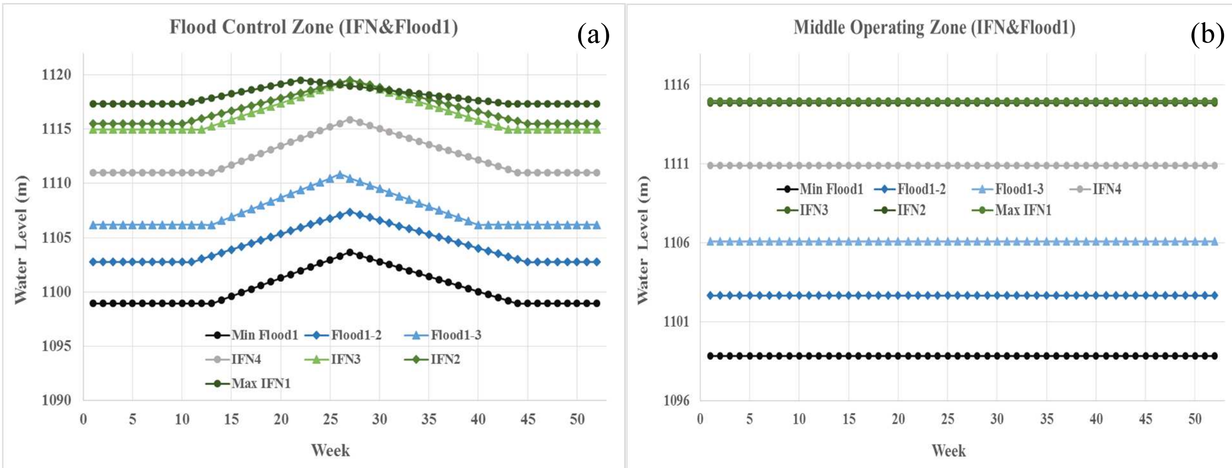

Figure 4.39: Flood control zones (a) and middle operating zones (b) of each point on the PFIF1

Figure 4-39 illustrates flood control zones (a) and middle operating zones (b) for each point on the PFIF1. The operating zones with minimum floodwater are same as the zones of the pink point on the PFEF1. The operating zones with maximum water allocated to IFN, also, are same as the zones of green point on the PFEI. Figure 4-40 depicts operating zones with the maximum water allocated to IFN (green curves) and the minimum floodwater (blue curves) on the PFIF1. However, other alternative operating zones extracted from PFIF1 are different from the two other Pareto front visualizations. In general, flood control zones, representing less floodwater, have lower initial level, start to increase in week 13th, and reach peak value in early June. But, flood zones, resulting in more water allocated to IFN, have much higher initial water level, and the slope of their rising limbs is very low. As can be seen in figure 4-39-b, the level of middle operating zones with lower floodwater is less than those with more water allocated to IFN.

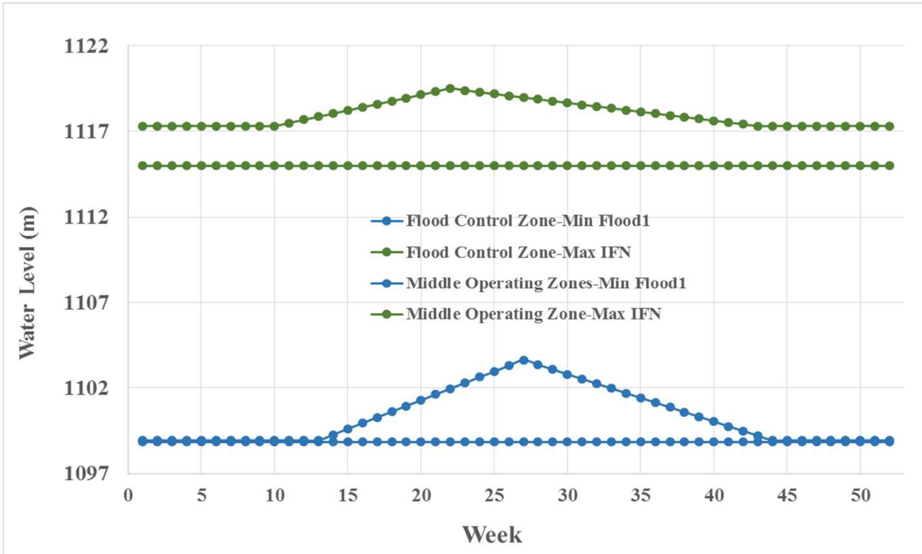

Figure 4.40: Operating zones with the maximum water allocated to IFN (green curves) and the minimum floodwater (blue curves) on the PFIF1

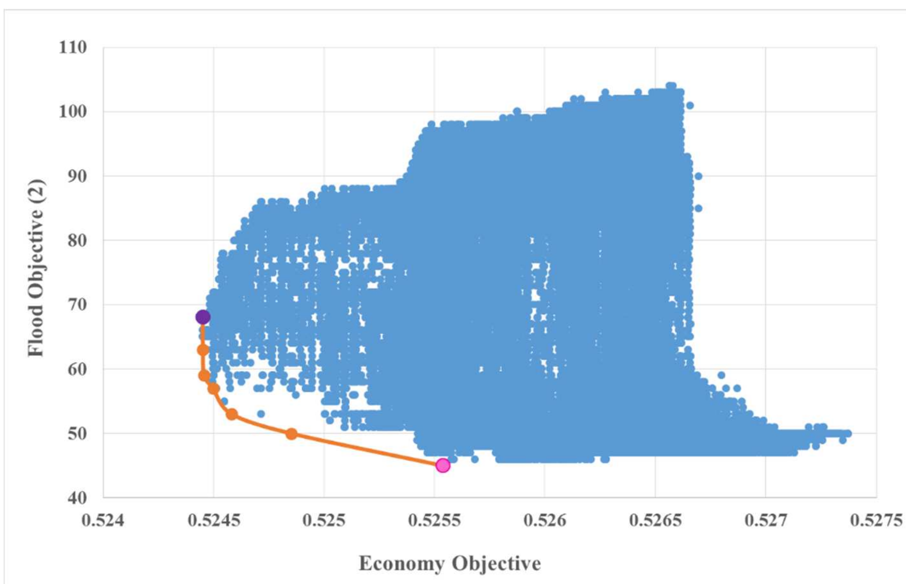

Figure 4.41: PSEF2 and PFEF2

Besides the amount of floodwater, flood frequency has a specific importance to protect the basin from flood damage. Flood objective function 2 has been defined to produce the sets of operating zones resulting in lower flood frequency. Figure 4-41 shows the Pareto surface (PS) and

Pareto front (PF) (orange line) of economy and flood 2 objective functions, PSEF2 and PFEF2.

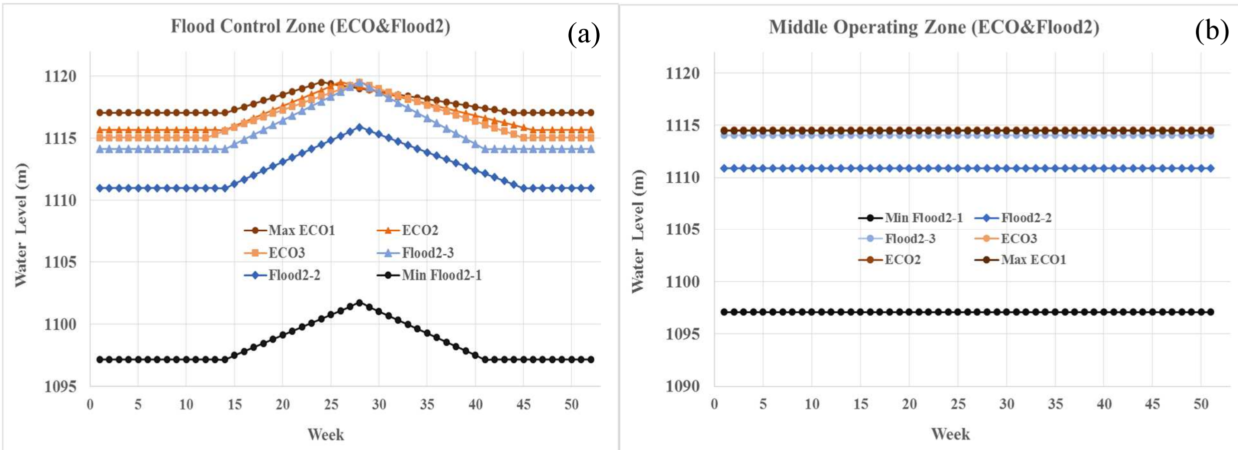

Figure 4.42: Flood control zones (a) and middle operating zones (b) of each point on the PFEF2

Flood control zones and middle operating zones causing points on PFEF2 have been shown in figure 4.42. The initial level of flood control zone with minimum flood frequency is 1097.18 m, about one m more than that with minimum floodwater. This curve begins to increase in week 14th, and in the middle of June touches the peak value of 1101.73, which is 1.9 m lower than the peak level of flood zone with minimum floodwater. It returns to the initial level three weeks earlier than the flood zone with minimum floodwater. Overall, the initial level of flood control zones resulting in less flood frequency is lower than those causing more economic benefit, and their middle operating zones are lower than those with more financial benefit. Operating zones with the maximum economic benefit (orange curves), producing the purple point on the PFEF2 and the minimum flood frequency (45 flood events in 74 years; blue curves), generating the pink point on the PFEF2, are depicted on figure 4.43.

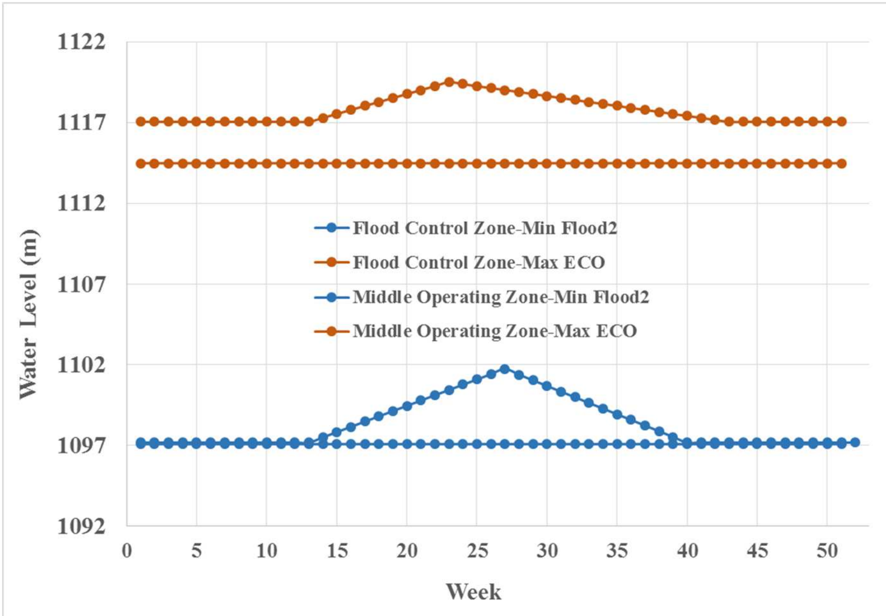

Figure 4.43: Operating zones with the maximum economic benefit (orange curves) and the minimum flood frequency (blue curves)

The Pareto surface (PSIF2) and Pareto front (PFIF2) of IFN and flood objective functions 2, can be seen in figure 4.44, and figure 4.45 shows flood control zones (a) and middle operating zones (b) of points on the PFIF2. In PFIF2, the initial level of flood control zones producing less flood frequency is lower than those resulting in more water allocated to IFN, like the points on the PFEF2 relationship. On the other hand, the middle operating zones creating less flood frequency are lower than those with more water allocated to IFN, like points on the PFEF2. Figure 4.46 depicts operating zones with the maximum water allocated to IFN (green curves), producing the green point on the PFIF2; and the minimum flood frequency (blue curves), generating the pink point on the PFIF2.

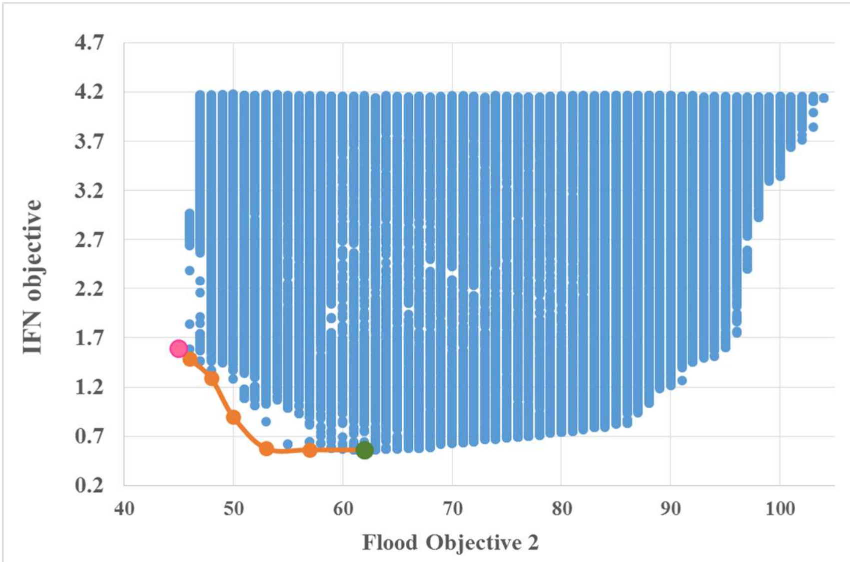

Figure 4.44: PSIF2 and PFIF2

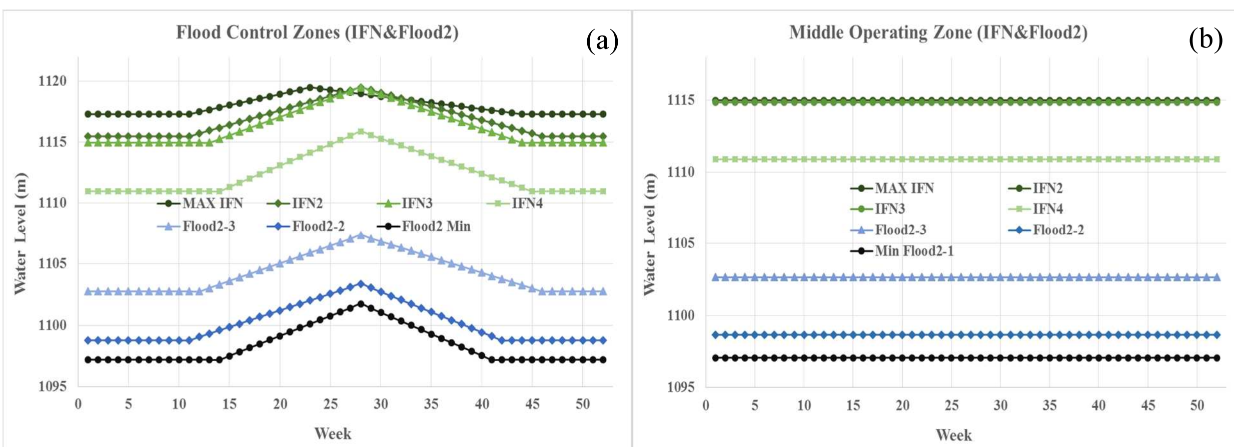

Figure 4.45: Flood control zones (a) and middle operating zones (b) of points on the PFIF2

4. 6. 3. Best Sets of Operating Zones for the Oldman River Reservoir

Applying the Pareto curve approach using four objective functions results in 18 different sets of operating zones for the Oldman River Reservoir. Which one of 18 sets of operating zones is chosen depends on decision makers' preference for higher economic benefit, water allocated to IFN or flood security. Four of these sets obtain the maximum economic benefit, maximum water

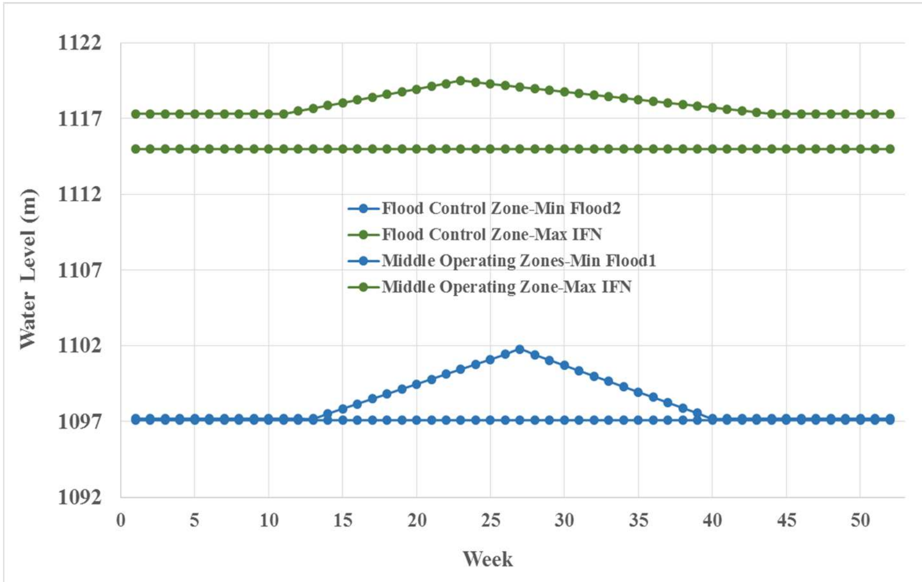

Figure 4.46: Operating zones with the maximum water allocate to IFN (green curves) and the minimum flood frequency (blue curves) on the PFIF2

allocation to IFN, and minimum floodwater, and flood frequency (figures 4.37, 4.40, 4.43, and 4.46). However, minimum floodwater, for instance, does not accompany with maximum economic benefit or maximum water allocated to IFN. The set of operating zones with minimum floodwater causes 16% less water allocated to IFN, and 5.7% less economic benefit, compared to sets resulting in the optimal economy and optimal water allocated to IFN. Therefore, the set of operating zones with minimum floodwater may cause lower economic benefit or water allocated to ecosystem in the basin. On the other hand, decision makers may not wish to sacrifice one of the objective functions and prefer to apply the set which results in the best solution in some overall sense. Hence, the sets of objectives, whose outcomes are close to the optimal solution, has been selected. 5 sets of 18, which do not cause major loss in four objective functions have been chosen and shown in figure 4.47. Orange curves will produce more economic benefit, blue curves will create more flood security, and green curves will result in more water allocated to IFN. Mint blue curves results in more water allocated to IFN and less flood, and purple curves do not make any one specific objective function very close to optimal, but cause the values of four objective functions to become almost equally close to the optimal solutions.

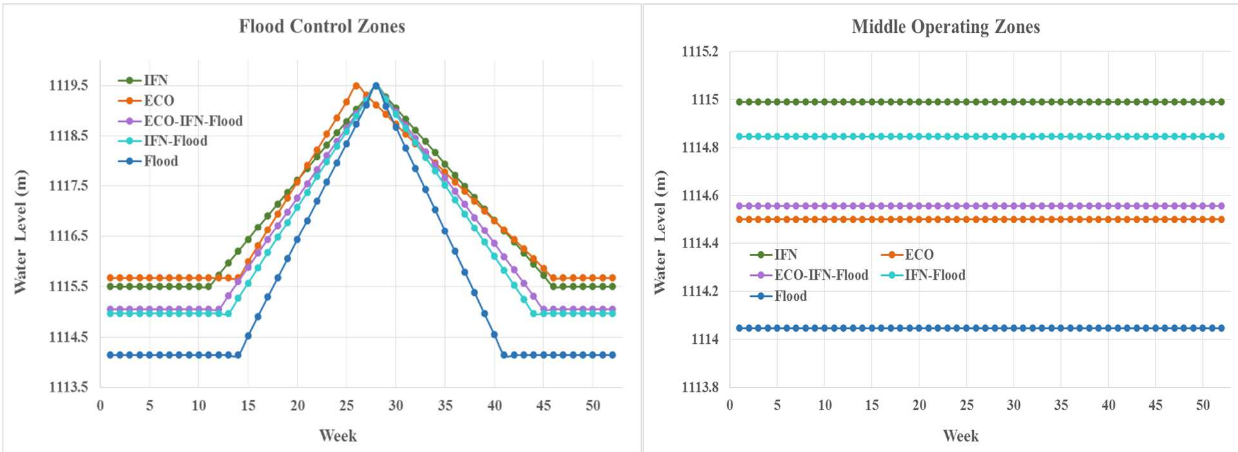

Figure 4.47: Five sets of operating zones, not causing major loss in four objective functions

The 5 selected sets of operating zones, however, can change under different hydrological or meteorological conditions. If the OMRB faces multiple floods, the selected sets may be changed and decision makers prefer to apply the operating zones with higher flood security, like darkest blue curves in figure 4.45. Overall, the hydrological or meteorological conditions of the basin and importance of economy or ecosystem dictate which set of operating zones should be chosen.

CHAPTER 5

CONCLUSION

In this chapter, first a summary of this study, including purpose, methodology, and the $SWAMP_{OM}$ model that has been developed here, is provided. Then the conclusions of results and analysis are presented, and finally possible future studies are discussed.

5. 1. Summary of the Study

This thesis focused on the development of an integrated water resources management (IWRM) model using the system dynamics (SD) approach for the Oldman River Basin (OMRB), located in southern Alberta, Canada. The SD approach can reflect interconnection between various components of a water system and represent dynamic loops controlling the complex behavior of the system. Since the OMRB is a semi-arid basin and faces multiple water resources challenges, including water shortage, uncertain water supply and water demand, flooding and drought, specific climatic and hydrological conditions, complex water governance and complex water systems, an IWRM model is required to address all these challenges and investigate their dynamic connections in the basin. Thus, an IWRM, called $SWAMP_{OM}$, including a water allocation model, dynamic irrigation demand, instream flow needs (IFN) and economic evaluation sub-models, has been developed for the OMRB. The water allocation sub-model is an emulation of an existing water resources management model, WRMM, which has been developed by Alberta Environment (2002). The data and operating policies required for the development of the water allocation sub-model have been derived from the WRMM. This sub-model meets current/future consumptive irrigation, industrial, and municipal demands, and satisfies non-consumptive ecosystem and hydropower generation demands, operating on a weekly time step. Meeting irrigation demands relies on the crop water requirement, which is affected by climate variations. Therefore, it should be estimated under varying climatic conditions, hence the need for the dynamic irrigation demand sub-model. This sub-model computes the crop water requirement for the main crops (barley, wheat, alfalfa, canola, flax, corn, sugar beet, potato, and beans) planted in 43 irrigation fields, which belong to five irrigation districts (Lethbridge Northern ID, St. Mary ID, Taber ID, Ross Creek ID, and Private ID). The sustainability of the aquatic ecosystem is another important concern in the basin. $SWAMP_{OM}$ calculates instream flow need (IFN) for six sections of the Oldman River using the Alberta Desktop method (Locke and Paul, 2011), and allocates enough water to rivers to meet IFN under different policy scenarios of uncertain water supply. In the OMRB the major water-related economic benefit, which is computed by the economic evaluation sub-model, is earned by agriculture and hydropower generation.

Water resources in the OMRB are highly regulated by infrastructure, like dams, of which the Oldman River Reservoir is the largest. This reservoir plays a critical role to meet the demands and keep a balance between the basin's economy and ecosystem while preventing floods and decreasing drought effects. This research also has aimed to produce different sets of Oldman Reservoir operation zones, resulting in trade-offs among four objective functions; the optimal economic benefit, water allocated to the ecosystem, and minimum floodwater and flood frequency; so that decision makers can decide how much water should be stored in the reservoir to meet a specific objective while not sacrificing others. A multi-objective performance assessment, using a Pareto curve approach, has been applied to identify the optimal trade-offs between the four objective functions, and define 18 different sets of operating zones. Each set results in an optimal value of one, or more objective functions, but a global optimum for all objectives together is not achievable. The preference of decision makers, for example for higher economic benefit, water allocated to IFN or flood security, can determine which set of operation zones should be selected.

5. 2. Conclusion of the Research Study

To conclude, the $SWAMP_{OM}$ can address most water challenges in the Oldman River Basin. $SWAMP_{OM}$ not only reflects the dynamic, loop-based interactions among different components of the water resource system, but it also facilitates analyzing the sensitivity of the water system to different "What-if" scenarios of water availability and IFN's policy. In addition, it enables the participation of decision makers in solving water problems in a basin. The following points can also be deduced:

I. The comparison between the $SWAMP_{OM}$'s results and WRMM's shows that $SWAMP_{OM}$ could reasonably represent all irrigation, industrial, municipal, ecosystem, and hydropower generation demands at a weekly time step. $SWAMP_{OM}$ could meet 86% of irrigation demands, 81% of industrial and municipal demand, 94% of ecosystem needs, and 100% of hydropower demands in the whole time period, from 1928 to 2001;

II. Comparison between the historical water levels and those computed by $SWAMP_{OM}$ for the Oldman River Reservoir shows that the two data series are better matched for higher water levels. However, the same comparison for the water released from the reservoir indicates higher correlation between historical low flows and those calculated by $SWAMP_{OM}$.

III. While there is a difference between irrigation demand estimated by WRMM and

$SWAMP_{OM}$, $SWAMP_{OM}$ could provide an adequate estimation of the crop water requirement under different hydrometeorological conditions. Based on the SWAMPOM's results, the average annual irrigation demand is 306 mm over the whole time period from 1928 to 2001 in the main irrigation districts, which increases to 714 mm in dry years and decreases to 92 mm in wet years. However, this value equals 319 mm in WRMM's database;

IV. $SWAMP_{OM}$ is promising as a tool to secure the aquatic ecosystem in the OMRB. The average weekly instream flow need of the Oldman River was estimated to be approximately 20.5 m^3/s by the Alberta Desktop method using the IFN sub-model. However, it is specified as 12.3 m3/s in WRMM, which applies the Fish Rule curves method. Under the current hydrometeorological conditions, $SWAMP_{OM}$ could meet entire IFN for more than 97% of weeks in the whole time period, from 1928 to 2001;

V. Average annual economic benefit, mostly earned by crop production and hydropower generation, was computed to be 192.5 M$ on average in the OMRB. It decreased to 82.8 M$ in very dry years, and increased to 328.6 M$ in very wet years;

VI. Increase in river flow resulted in a large effect on water allocated to IFNs, specifically in wet years, and an influence on the basin's economy in dry years, in particular. However, changing the IFN percent of natural flow component did not have a significant influence on both economic benefits and water allocated to IFN; and

VII. Water allocation and water-related economy in the OMRB are sensitive to the Oldman River Reservoir operation. Using a Pareto curve approach under four objective functions of maximum economic benefit, maximum water allocated to the ecosystem, minimum floodwater, and minimum flood frequency, 18 different, optimal, or close to optimal sets of operating zones were calculated for the Reservoir. Operating zones is chosen based on decision makers' preference for higher economic benefit, water allocated to IFN or flood protection. However, the set of operating zones with minimum floodwater caused 11 less flood events; the operating zones with maximum economy resulted in 4.1% more financial gain; and the zones with maximum water allocated to IFN led to 10.1% more ecosystem protection in the whole 74 years, compared to current zones.

5. 3. Future Work

Some of the possible additional research studies, associated with the $SWAPM_{OM}$ and optimal operating zones, are as follows:

I. Since $SWAMP_{OM}$ is an emulation of WRMM, and hence simplified to some extent, only some of the WRMM's polices (for example, penalty zones) have been applied in the $SWAMP_{OM}$. Therefore, the two model results are not quite matched for some water components. Adding all WRMM's policies would be useful to increase the correlation between two model results;

II. While $SWAMP_{OM}$ is an integrated water resources management model, it does not model all the basin's characteristics. Hydrological modeling and groundwater management can be added to the $SWAMP_{OM}$, in order to more comprehensively address water management in the basin;

III. Water resources and water management in the Oldman, Bow, Red Deer, and South Saskatchewan are connected together. Developing SWAMP for other basins, and linking them can be the next step to have holistic water management in three prairie provinces of Alberta, Saskatchewan, and Manitoba (Currently SWAMP has been developed for Oldman, Bow, and Saskatchewan portion of South Saskatchewan river basins);

IV. In this study, sustainable economy, ecosystem protection and flood protection were assessed using the Pareto approach. However, another important concern in the basin is drought. Defining a drought objective function and minimizing the drought effects in the basin could be a possible future scope.

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Appendix A

All equations which have been used in the dynamic irrigation demand sub-model, but have not been mentioned in chapter 3, section 3. 4. 2, are provided here. The sub-model applies the modified Penman equation to calculate the reference evapotranspiration which is:

$$ET_0 = \frac{\left(0.408\times\Delta\times(\mathrm{Rn}-\mathrm{G})\right)+\gamma\times\left(\frac{1600}{T+273}\right)\times u_2\times(es-ea)}{\Delta+(\gamma\times(1+0.38\times u_2))} \quad \text{(A.1)}$$

where Δ is the slope of the saturation vapor pressure-temperature curve (kPa/^{o}C), Rn is the net radiation (MJ/m^2/day), G is the soil heat flux (MJ/m^2/day) and assumed equal to zero, γ is the psychrometric constant (kPa/^{o}C), T is mean daily temperature (^{o}C), and u_2 is the wind speed at the height of 2 m (m/s). Parameters applied in equation (A.1) can be calculated using equations below:

$$\Delta = \left(0.2 * \left(\left((0.00738 \times T_{Mean}) + 0.8072\right)^7\right)\right) - 0.00116 \quad \text{(A.2)}$$

$$R_n = \frac{86400}{1000000} \times \left(\frac{0.63\times24\times1000\times Solar\ Radiation}{86400} - 40\right) \quad \text{(A.3)}$$

$$u_2 = u_{10} \times \left(\frac{2}{10}\right)^{0.2} \quad \text{(A.4)}$$

$$\gamma = \frac{Specific\ Heat\times Atmospheric\ Pressure}{0.622\times Latent\ Heat\ of\ Vapourization} \quad \text{(A.5)}$$

Specific Heat =0.001013 (A.6)

$$Atmospheric\ Pressure = 101.3 \times \left(\frac{\left((T_{Mean}+273.16)-(0.0065\times Elevation)\right)}{(T_{Mean}+273.16)}\right)^{5.256} \quad \text{(A.7)}$$

$$Latent\ Heat\ of\ Vapourization = 2.501 - (0.00236 \times T_{Mean}) \quad \text{(A.8)}$$

$$Vapour\ Pressure = e_a = RH \times Saturated\ Vapour\ Pressure \quad \text{(A.9)}$$

$$RH = \frac{10^{\left(\frac{7.5\times T_{Dew\ Point}}{237.7+T_{Dew\ Point}}\right)}}{10^{\left(\frac{7.5\times T_{Mean}}{237.7+T_{Mean}}\right)}} \quad \text{(A.10)}$$

$$Saturated\ Vapour\ Pressure = e_s = EXP\left(52.58 - \left(\frac{6790.5}{T_{Mean}+273.15}\right) - 5.03 \times LN(T_{Mean} + 273.15)\right) \quad \text{(A.11)}$$

To estimate the infiltration (IR_t) and the runoff (R_t) applied in the equation (3.5), following formulas were used:

$IR_t = 0.9177 + 1.811 \times LN\ (RF_I \times 0.0393701) - 0.0097 \times LN\ (RF_I \times 0.0393701) \times (SM_t/\ FC_{tc}\ ) \times 100)$ (A.12)

$R_t = RF_I – (0.9177 + 1.811 \times LN\ (RF_I \times 0.0393701) - 0.0097 \times LN\ (RF_I \times 0.0393701) \times (SM_t/\ FC_{tc}\ ) \times 100))$ (A.13)

where RF_I is intense rainfall.

Appendix B

Irrigation demands of five districts in the Oldman River Basin from 1928 to 2001 calculated by dynamic irrigation demand sub-model has been presented here. Figure B.1 shows irrigation demand of Ross Creek ID (RCID), figure B.2 shows irrigation demand of the Northern Lethbridge irrigation district (NLID), figure B.3 depicts irrigation demand of St. Mary River and Taber IDs (SMRID&TID), and figure B.4 indicates irrigation demand of private ID (PID), from 1928 to 1995.

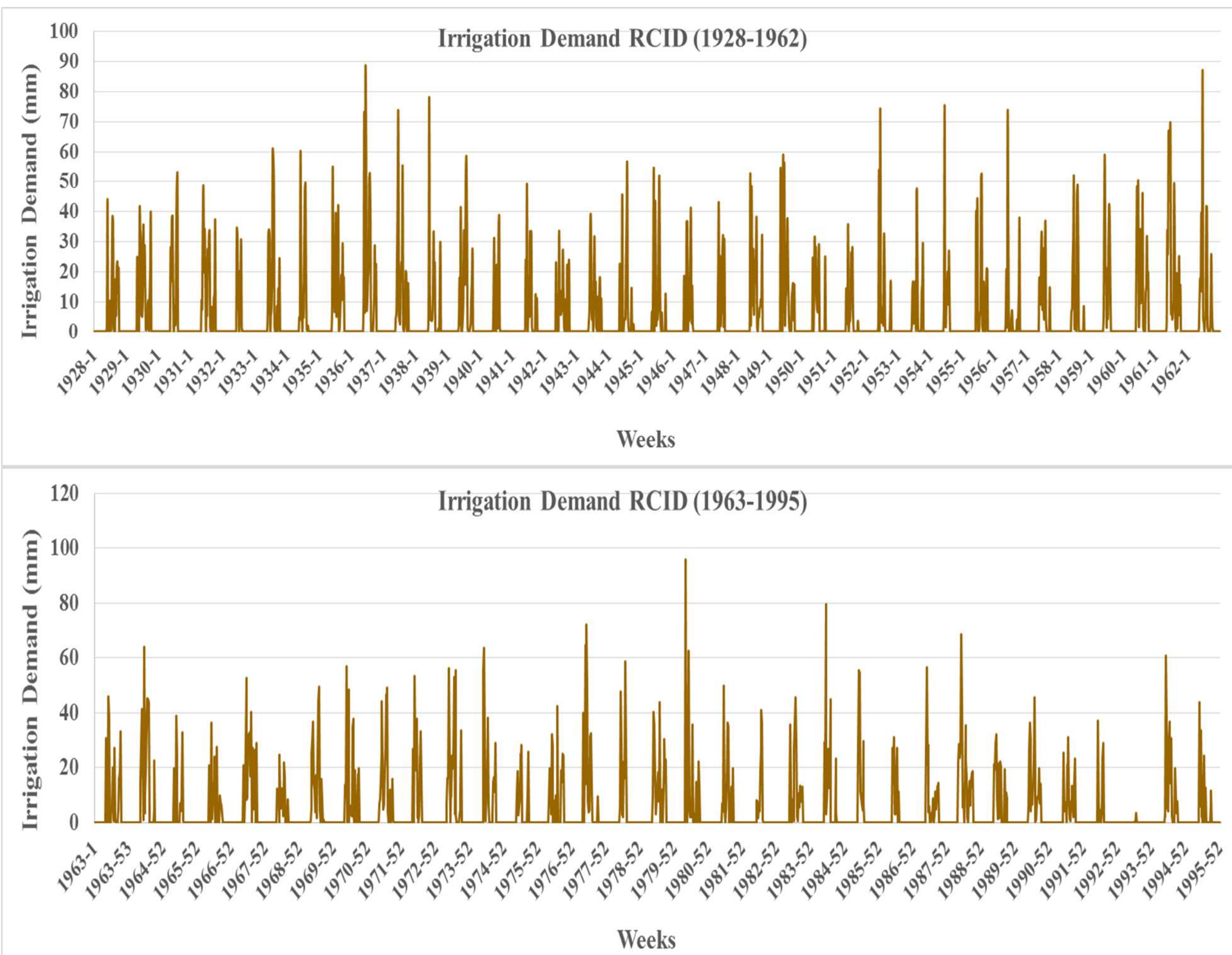

Figure B.1: Irrigation demand of Ross Creek ID (RCID) from 1928 to 1995

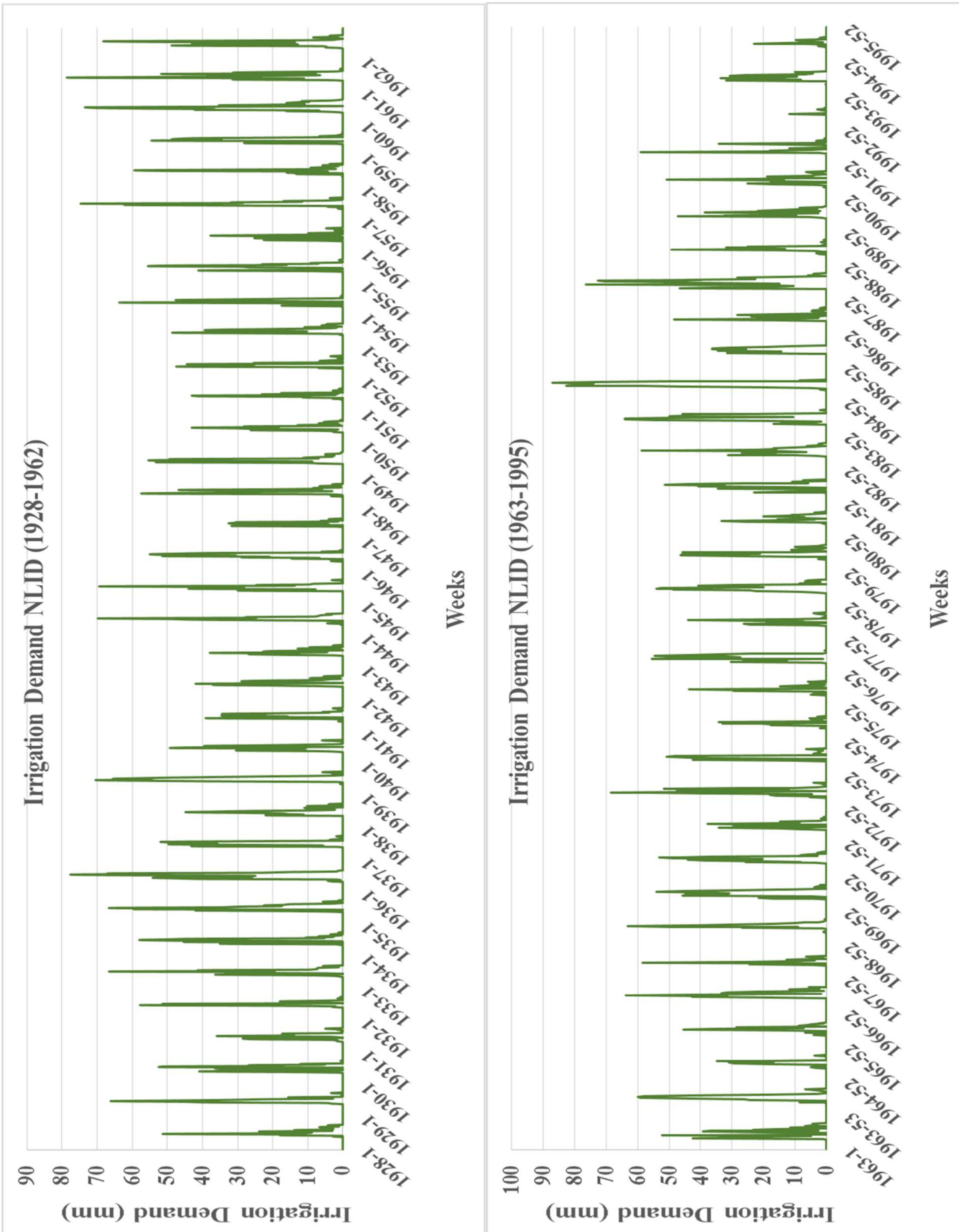

Figure B.2: Irrigation demand of Northern Lethbridge irrigation district (NLID) from 1928 to 1995

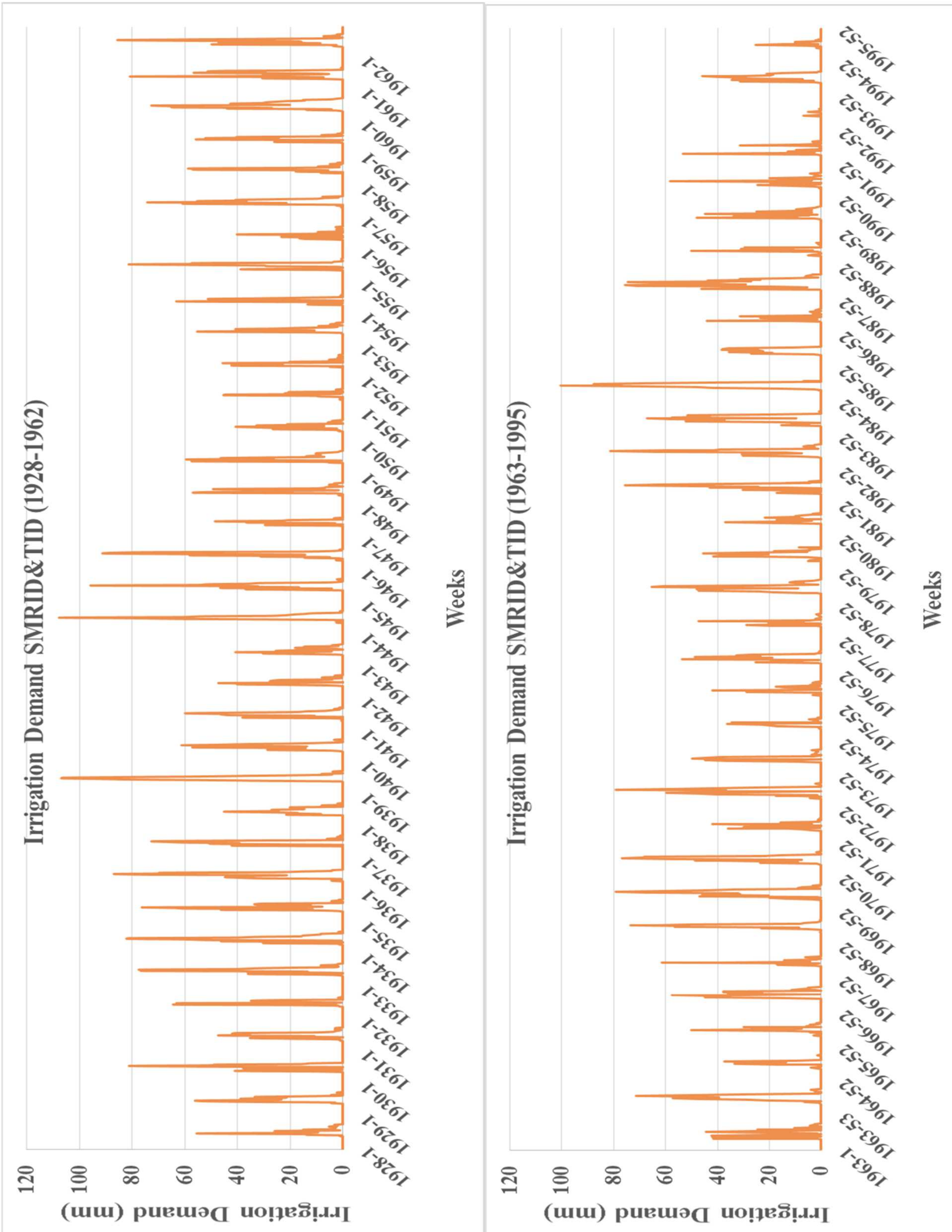

Figure B.3: Irrigation demand of St. Mary River and Taber IDs (SMRID&TID) from 1928 to 1995

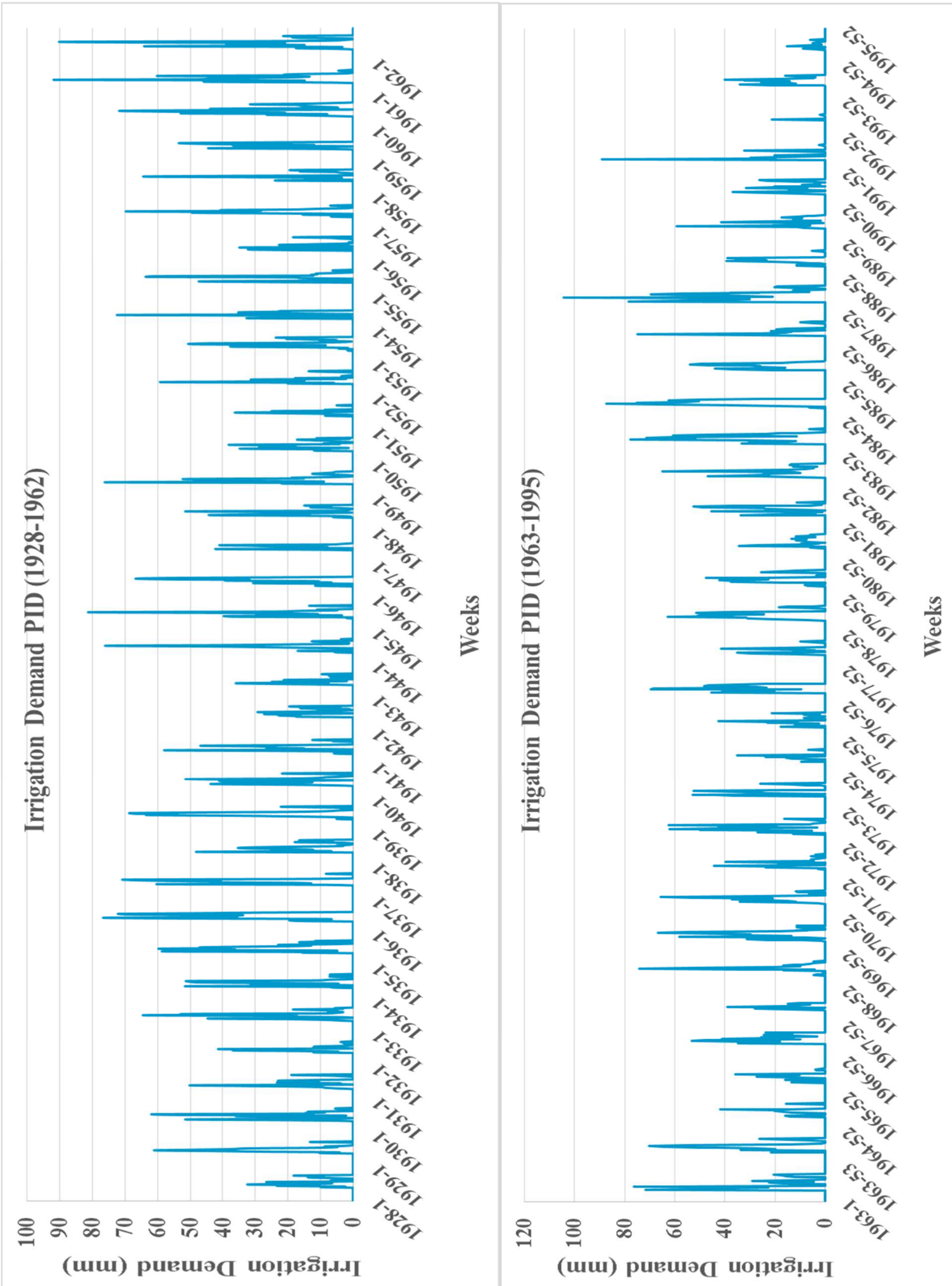

Figure B.4: Irrigation demand of private ID (PID) from 1928 to 1995