INTEGRATED WATER RESOURCES MANAGEMENT IN A TRANSBOUNDARY RIVER BASIN: MODEL DEVELOPMENT AND SENSITIVITY ANALYSIS

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By

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ABSTRACT

Traditional water resources management in transboundary river basins is often fragmented by political boundaries. This fragmentation cannot effectively address the challenges induced by increasing anthropogenic activities and climate change, which follow the river basin boundary rather than the political borders. The basin-scale water management model in such cases is a useful tool to investigate the impacts of these challenges over the social, economic, and environmental dimensions of water resources management. The Saskatchewan River Basin (SaskRB) is a sizeable transboundary river system in Canada, facing several water security challenges. Climate change and growing hydrological variability further accentuate these challenges by increasing uncertainty in supply and demand. The fragmentation of water resources management by provincial administrations, in principle, can hinder the process of basin-level water resources planning and management. An integrated basin-scale water management model can help to manage water resources both at the sub-basin and basin-scale effectively.

The present study first developed seven water management models for different regions of the SaskRB within the MODSIM system, which is a well-established modelling platform for river basin management and decision support. Next, these models (called "sub-models" hereafter), which simulate local water management and allocation rules in their respective regions, were integrated into one unified platform to develop an integrated water management model for the SaskRB (IWMSask). IWMSask was validated based on observed data and previous modeling work in the basin. IWMSask was then applied under changing conditions of demand and supply to assess the sensitivities of the water resources system. Three different scenarios of change were considered, which include a 10% decrease in streamflow (C1), a 10% increase in irrigation demand (C2), and a combination of C1 and C2 (C3). The results showed that the IWMSask can represent the entire system under the current and future water management infrastructure and climate conditions, thereby providing a platform for the stakeholders and decision-makers to understand the interconnected complexities of the entire system, vulnerabilities, and implications of policy change in one point for the rest of the system. IWMSask provides a helpful tool to investigate basin-level issues, e.g., the impact of natural and anthropogenic changes on the economy, society, and environment. It further enables the users to examine alternative policy options and discover trade-offs in the mitigation of the impacts of climate change.

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I am deeply indebted to the Global Institute for Water Security for financial support and assistance, without which I would not have been able to complete this research and thesis.

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DEDICATION

This dissertation is dedicated to my beloved mother, Begum Ummea Salma, who is my inspiration and my mentor. Without her enormous personal sacrifice and unconditional love, I would have never become the individual that I am today.

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LIST OF ABBREVIATIONS

AAFRD	Alberta Agriculture, Food and Rural Development
AB	Alberta
ACE	Area-Capacity-Elevation
AEP	Alberta Environment and Parks
AID	Aetna Irrigation District
AMA	Annual Moving Average
AUC	Alberta Utilities Commission
BTAP	Blood Tribe Agriculture Project
Dam^3	Cubic Decameter
DSL	Dead Storage Level
DSS	Decision Support Systems
ECDF	Empirical Cumulative Distribution Function
EFRs	Environmental Flow Requirements
ENSO	El Niño Southern Oscillation
FSL	Full Supply Level
GoA	Government of Alberta
GUI	Graphical User Interface
HBDF	Hydrometeorologic Base Data File
HRDP	Highwood River Diversion Plan
IF	Incremental Flow
IFN	Instream Flow Need
IJC	International Joint Commission
IO	Instream Objectives
IP	Irricana Power
IRM	Irrigation Requirement Model
Irr	Irrigation
IWMSask	Integrated Water Management Model for the SaskRB
km^2	Square Kilometre
LID	Leavitt Irrigation District

m	Meter
m^3/s	Cubic Meter Per Second
MAI	Mean Annual Inflow
MB	Manitoba
MCM	Million Cubic Meter
MID	Magrath Irrigation District
mm	Millimeter
MOL	Maximum Operating Level
MT	Montana
MVID	Mountain View Irrigation District
MW	Major Withdrawal
MW	MegaWatt
N/A	Not Available
NSE	Nash Sutcliffe efficiency
NSR	North Saskatchewan River
NSR-AB	North Saskatchewan River in Alberta
NSRB	North Saskatchewan River Basin
NSRB-AB	North Saskatchewan River Basin in Alberta
NSRB-SK	North Saskatchewan River Basin in Saskatchewan
NSR-SK	North Saskatchewan River in Saskatchewan
PAC	Public Advisory Committee
PFRA	Prairie Farm Rehabilitation Administration
PPWB	Prairie Provinces Water Board
PWSS	Public Works, Supply and Services
RF	Return Flow
RIBASIM	River Basin Simulation Model
RID	Raymond Irrigation District
RMSE	Root Mean Squared Error
RR	Run-of-the-River
SaskR	Saskatchewan River
SaskRB	Saskatchewan River Basin

SaskRB-MB	Saskatchewan River Basin in Manitoba
SCF	Simulation Control File
SK	Saskatchewan
SMRID	St. Mary River Irrigation District
SRD	Saskatchewan River Delta
SSR	South Saskatchewan River
SSR-AB	South Saskatchewan River in Alberta
SSRB	South Saskatchewan River Basin
SSRB-AB	South Saskatchewan River Basin in Alberta
SSRB-Database	South Saskatchewan River Basin Weekly Natural Flow Database
SSRB-SK	South Saskatchewan River Basin in Saskatchewan
SSROM	South Saskatchewan River Operational Model
SSR-SK	South Saskatchewan River in Saskatchewan
STRIBS	Southern Tributaries
TAC	TransAlta Corporation
TAU	TransAlta Utilities
TAW	Total Available Water
TID	Taber Irrigation District
TOF	Total Outflow
TRB	Transboundary River Basin
UID	United Irrigation District
VARS	Variogram Analysis of Response Surface
WEAP	Water Evaluation and Planning
WRIMS	Water Resource Integrated Modeling System
WRMM	Water Resources Management Model
WSA	Saskatchewan Water Security Agency
WSB	Water Stewardship and Biodiversity

1 Chapter 01: Introduction

1.1 Background and Problem Definition

Water resources management is complex, particularly in large transboundary river basins (TRBs), where multiple jurisdictions are involved in resource allocation decision-making processes. The complexity can be further aggravated by the mismanagement and unsustainable exploitation of the limited freshwater resources, which often leads to conflict between different users and uses of water (Prakash, 2007). To satisfy the needs of different water user groups such as municipal, industrial, agricultural, engineering structures such as dams and diversions are often constructed. Such constructions have long-term impacts on downstream flows and the aquatic environment as well as water management strategies (Mary *et al.*, 1996; Magilligan and Nislow, 2005; Graf, 2006; Pal, 2016; Li *et al.*, 2017; Timpe and Kaplan, 2017; Granzotti *et al.*, 2018). Extensive changes in land-use also have a significant impact on water security (Qiu *et al.*, 2012). Apart from anthropogenic activities, climate change has altered streamflow and properties of associated hydro-meteorological variables which are driving water availability in many parts of the world (Vörösmarty *et al.*, 2000; Groisman *et al.*, 2001; Nijssen *et al.*, 2001; Oki and Kanae, 2006; Viviroli *et al.*, 2011; Mann and Gleick, 2015; Gosling and Arnell, 2016; Kirby *et al.*, 2016), and has increased the complexity of water resources management (Wheater and Gober, 2015).

Traditionally, in large-scale TRBs, water resources are managed by local jurisdictions at sub-basin scales, which fragments the process of river-basin resource allocation. This water management approach within local jurisdictional boundaries can provide short-term solutions to local water problems and economic growth. However, such an approach cannot provide a long-term, river basin-scale planning platform to analyze the impacts of the changing climate conditions and increasing anthropogenic activities, which requires analyses that follow the full river basin boundaries (Han *et al*., 2013).

The Saskatchewan River Basin (SaskRB), located in western Canada, is one of the largest and most complex transboundary river systems in the world. The basin has an area of 405,864 km^2 and lies in three Canadian provinces of Alberta (AB), Saskatchewan (SK), and Manitoba (MB), and one US state, Montana (MT). The SaskRB, in particular the southern part of the basin, is the hub for agricultural activities of all kinds and plays a significant role in the provincial and federal economy (Islam and Gan, 2016). The hydropower in the SaskRB also has strategic importance for energy security in this region. The rapid growth of population and industrialization coupled with irrigation expansion is resulting in an unprecedented growth in water demand, which is putting pressure on the limited freshwater resources of this basin. For instance, in the southern portion of the SaskRB, particularly in Alberta, water allocation has reached its limit, and the provincial government has already restricted further allocation of water to new users (Alberta Environment, 2003).

The water use and allocation in the SaskRB mostly rely on the surface water resources, which strongly depend on the streamflow regimes (Pomeroy *et al.*, 2005). The Saskatchewan River and its tributaries receive water mainly from snowpack and glaciers of the Canadian Rocky Mountains, which are subject to significant change due to climate change and hydrological variability (DeBeer *et al.*, 2016). Portions of the SaskRB have already been affected by the change in water availability (Rood *et al.*, 2008). Apart from climate change, anthropogenic activities such as the construction of a large number of reservoirs (59 reservoirs), hydropower plants (29 plants), and irrigation expansion in different regions, have significantly affected the water availability in many parts of the system. Such changes in water availability have a profound impact on water allocation and decision making regarding social, economic, and environmental objectives.

The water resources management in the SaskRB is handled within provincial borders. The transboundary water resources are managed by the apportionment agreements, e.g., the Master Agreement on Apportionment (1969) between the Prairie Provinces, and the 1921 Order of the International Joint Commission (IJC) between Canada and the US. The provincial water resources policy and plans are limited to political borders after satisfying the apportionment commitments. Such fragmentation of water resources management complicates the process of regional planning and development, as well as policy analysis and decision making under changing conditions. To address these concerns, integrated, river-basin water management modeling tools can assist in resource allocation planning across scales from local and sub-basin scales to basin-wide scales. Such an integrated management platform can synthesize essential information for policymakers to investigate alternative resource allocation policies and other types of decisions.

1.2 The Objective of the Study

The overall objective of the study is to develop a water management modeling tool for the SaskRB to facilitate improved understanding of the entire system and to provide a basin-scale decision-support platform regarding water allocation. The objective was achieved by fulfilling the following sub-objectives:

1) To develop water allocation models for each of the sub-basins of the SaskRB, which could be used for sub-basin scale water resources management and planning;
2) To develop an integrated water management model for the SaskRB, which would be useful for basin-scale water management and planning and policy investigation; and
3) To assess the sensitivity of the SaskRB water resources system to changing flow and demand conditions by utilizing the developed integrated water management model.

1.3 Organization of the Thesis

The thesis consists of three chapters and eight appendices. Chapter 1 outlines the water management challenges in the SaskRB and the knowledge gaps, as well as the research objectives of this thesis. In response to the research objectives, one research manuscript is presented in Chapter 2, which provides the details of water allocation model development, validation strategy, and results of all developed sub-models as well as the integrated water management model, and the sensitivity of the SaskRB water resources system under changing streamflow and irrigation demand conditions. Chapter 3 summarizes the findings of the research and outlines the limitations of this study and suggestions for future developments.

Appendix A outlines the theoretical background of the type of water management models used in the current study. An overview summary of the water allocation model development process is presented in Appendix B. Details of the system properties considered for water allocation model development for different areas of the SaskRB are presented in Appendix C (TransAlta Utilities (TAU)), Appendix D (Highwood River Diversion Plan (HRDP)), Appendix E (Southern Tributaries (STRIBS)), Appendix F (North Saskatchewan River Basin in Alberta (NSR-AB)), and Appendix G (North Saskatchewan River Basin in Saskatchewan (NSR-SK)). Appendix H explains the integration process of the basin-scale water management model development.

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2 Chapter 02: Integrated Water Resources Modeling for a Complex Transboundary River System

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Possible Submission

A modified version of this chapter will be submitted to the Journal of Water Resources Planning and Management or Journal of Water Resources Management.

Contribution of the M.Sc. Candidate

The M.Sc. candidate collected all necessary information from different sources, developed and analyzed all water allocation and management models under the supervision of Dr. Saman Razavi. Dr. Amin Elshorbagy and Dr. Howard Wheater provided advice on various aspects of the work. Dr. Nhu Cuong Do provided technical support to run the computer program. Dr. Nhu Cuong Do also prepared the schematic map for the Saskatchewan River Basin water resources system based on the materials and information provided by the M.Sc. candidate. The candidate also drafted the text of the manuscript. Dr. Saman Razavi, Dr. Amin Elshorbagy, Dr. Howard Wheater and Dr. Andrew Slaughter offered critical review and editorial guidance.

2.1 Abstract

Increasing anthropogenic activities and climate change have raised the attention to basin-scale water resources management, particularly in transboundary river systems. The Saskatchewan River Basin (SaskRB) in western Canada is a complex transboundary river basin that is facing several water security challenges. The fragmentation in the operation and management of the basin, in principle, can hinder the process of basin-level water resources planning and management. Integrated management can lead to more efficient use of resources in the whole basin. Herein, a total of seven water allocation models are developed for different regions of the SaskRB (sub-models), and subsequently, they were combined to develop an integrated water management model for the SaskRB (IWMSask). The IWMSask was also applied for three different scenarios of change, which include a 10% decrease in streamflow (C1), a 10% increase in irrigation demand (C2), and a combination of C1 and C2 (C3), and analyzed to determine the sensitivity of the SaskRB water resources system. The sub-models are useful to investigate local water security issues while the IWMSask is an effective tool for transboundary water resources management.

2.2 Introduction

Rapid socio-economic development and population expansion have resulted in a dramatic change to both the quantity and quality of global freshwater resources. This pressure on water resources is being exacerbated by increased anthropogenic activities and mismanagement (Prakash, 2007), and has a long-term impact on downstream natural streamflow and aquatic environment (Mary *et al.*, 1996; Magilligan and Nislow, 2005; Graf, 2006; Pal, 2016; Li *et al.*, 2017; Timpe and Kaplan, 2017; Granzotti *et al.*, 2018). Apart from anthropogenic activities, climate change has resulted in altered streamflow and properties of associated hydro-meteorological variables in many parts of the world (Vörösmarty *et al.*, 2000; Groisman *et al.*, 2001; Nijssen *et al.*, 2001; Oki and Kanae, 2006; Viviroli *et al.*, 2011; Mann and Gleick, 2015; Gosling and Arnell, 2016; Kirby *et al.*, 2016), and has increased the complexity of water resources management (Wheater and Gober, 2015).

Effective water resources management, particularly in large transboundary river basins (TRBs), is challenging due to the existence of multiple administrative units in the decision-making process with potentially conflicting interests (Kashyap, 2004). Consequently, water resources are often shared by transboundary water agreements and managed by local regulatory frameworks, which can result in some fragmentation in the management process. Such fragmentation can, in principle, raise difficulties in effective water quality and quantity management. Kim *et al.* (2015) showed that stream water quality declines more rapidly where watersheds are shared and managed by multiple jurisdictions. According to Yaffee (1997), fragmentation in management structure is one of the main reasons for recurrent failures of environmental policy. In addition, fragmentation of management according to political instead of river basin boundaries can result in competition rather than cooperation between different administrations, leading to political disputes which have significant economic, social, and environmental consequences (Yoffe *et al.*, 2003; Kim and Jurey, 2013; Choudhury and Islam, 2015). In contrast, basin-wide water resources management can effectively assess the influence of anthropogenic activities on the environment (Kim *et al.*, 2015), establish water accounting for riparian jurisdictions (Kim and Jurey, 2013), trace consumption of different competitive water users, and investigate alternative policy options about water allocation, pricing, and infrastructure development (Cai *et al.*, 2006).

The Saskatchewan River Basin (SaskRB), located in western Canada, is a complex transboundary system (Figure 2.1). Since the basin transcends multiple provincial and international jurisdictions, water resources in the basin have traditionally been managed multiple units independently, each employing its modeling platform and policies while satisfying the transboundary apportionment needs. SaskRB receives a majority of its water from snowpack and glaciers of the Canadian Rocky Mountains, which are highly vulnerable to climate change (DeBeer *et al.*, 2016). Some portions of the SaskRB in the Alberta province are already affected by climate change-induced regime change (Rood *et al.*, 2008), which also has an impact on the downstream water resources system (Nazemi *et al.*, 2013). Hydrological extremes (e.g., flood and drought) have historically had severe consequences on the environment, economy, and society of this region (Wheater and Gober, 2015), and due to climate change such extreme events might be frequent in future (Farjad *et al.*, 2017; Asong *et al.*, 2018). On the other hand, increasing anthropogenic activities, notably building a large number of reservoirs (59), hydropower plants (29), diversion works and irrigation projects, have significantly affected the streamflow regimes and downstream environment (Jacques *et al.*, 2010; Wheater and Gober, 2013; Gober and Wheater, 2014; Xu *et al.*, 2014). These changes in the hydrological system combined with rapidly increasing human activities can affect regional economic development, as well as social, cultural, and environmental resources. A basin-scale transboundary water management model can be an important tool to understand the integrated response of the system to any hydrological variability or changes of operational policy and can play a crucial role in investigating different policy decisions for maximizing economic benefits while meeting environmental needs.

Although there has been increasing attention to water management modeling for the SaskRB, previous attempts have generally been limited to local scales and objectives. For instance, Hassanzadeh *et al.* (2014) proposed a modeling platform for the South Saskatchewan River (SSR) basin within the borders of the Saskatchewan province, by incorporating irrigation demand and cost-revenue evaluation sub-models. Gonda (2015) and Safa (2015) extended this work for the Bow and Oldman river sub-basins in Alberta, respectively. Islam and Gan (2016) adopted a water allocation model developed by Alberta Environment and Parks for the province of Alberta, called the Water Resources Management Model (WRMM), to assess the potential combined impact of climate change and El Niño Southern Oscillation (ENSO) on different water user groups in the SSR basin. Alberta WaterSMART developed the South Saskatchewan River Operational Model (SSROM) to evaluate net benefits of strategies across the SSR basin in Alberta only and considered a range of scenarios of hydroclimatic variability and extremes (WaterSMART, 2016). Similarly, a large number of water management modeling and policy analysis studies are available in the literature which focused on the SSR basin only (Wang et al., 2008b, 2008a; Cutlac and Horbulyk, 2011; Hipel et al., 2013; Sheer et al., 2013; Ali and Klein, 2014; Islam and Gan, 2014; Weber and Cutlac, 2014; Healy, 2015; Yassin et al., 2019). To date, there has been no comprehensive attempt to represent the complex water management system and processes for the entire SaskRB in one integrated platform.

The objective of this study is to develop an integrated water management model for the SaskRB (IWMSask) and examine the sensitivity of the system components to changing conditions which may arise due to human activities and climate change. Moreover, the model can be used in practice by decision-makers and stakeholders at local and river basin scales to answer a range of policy questions.

2.3 Study Area: the Saskatchewan River Basin (SaskRB)

The Saskatchewan River Basin (SaskRB) has a total area of 405,864 km^2 and transcends three Canadian provinces of Alberta (AB), Saskatchewan (SK), and Manitoba (MB) and the US State of Montana (MT) (Figure 2.1). The basin is of social, economic, and ecological importance as it contains many provincial park areas, major cities such as Calgary, Edmonton, and Saskatoon as well as several First Nation communities, large irrigated agricultural areas, and many industries, supporting a total population of three million people. The SaskRB includes two principal tributaries, the North and South Saskatchewan Rivers (NSR and SSR, respectively). The headwaters of both of these tributaries are in the east-facing slopes of the Rocky Mountains. The rivers flow east-northeastward across the Canadian Prairies, subsequently merging in SK to form the Saskatchewan River (SaskR). At the MB-SK border, the river forms the Saskatchewan River Delta (SRD), which empties into Lake Winnipeg in MB. The Oldman, Bow, and Red Deer rivers comprise the main tributaries of the SSR, whereas the Brazeau and Clearwater rivers are the major headwater tributaries of the NSR.

The principal regulatory authorities for water management and decision making in the SaskRB include Alberta Environment and Parks (AEP), Saskatchewan Water Security Agency (WSA), and Water Stewardship and Biodiversity (WSB) in the AB, SK, and MB provinces, respectively. The provinces are responsible for ensuring equitable distribution of inter-provincial streams under the 1969 Master Agreement on Apportionment. This agreement is overseen by the Prairie Provinces Water Board (PPWB), an intergovernmental framework, with representatives from the three Prairie Provinces (AB, SK, and MB) and the Federal Government (Prairie Provinces Water Board, 1969). According to this agreement, the upstream province must pass one-half of the annual natural flow that it receives to the downstream province. Additional constraints are added to the SSR, including the requirement that AB passes a minimum of 42.5 m^3/s downstream to the SK province. An international water-sharing treaty, known as the International Joint Commission (IJC) 1921 Order, is also in place between Canada and the US, to manage water sharing for the transboundary St. Mary River (a tributary of the Oldman River). According to IJC-1921 order, AB must receive 50% of the natural flow of the St. Mary River during the non-irrigation season, and 75% of the first 18.86 m^3/s of the natural flow and 50% of any excess over 18.86 m^3/s during the irrigation season (Halliday and Faveri, 2009). Also, based on the 1930 Constitution Act, the Federal Government is involved in provincial water resources affairs by improving rural water supply facilities, water quality monitoring, fisheries and navigation management, and water rights of First Nation communities (Halliday, 2009).

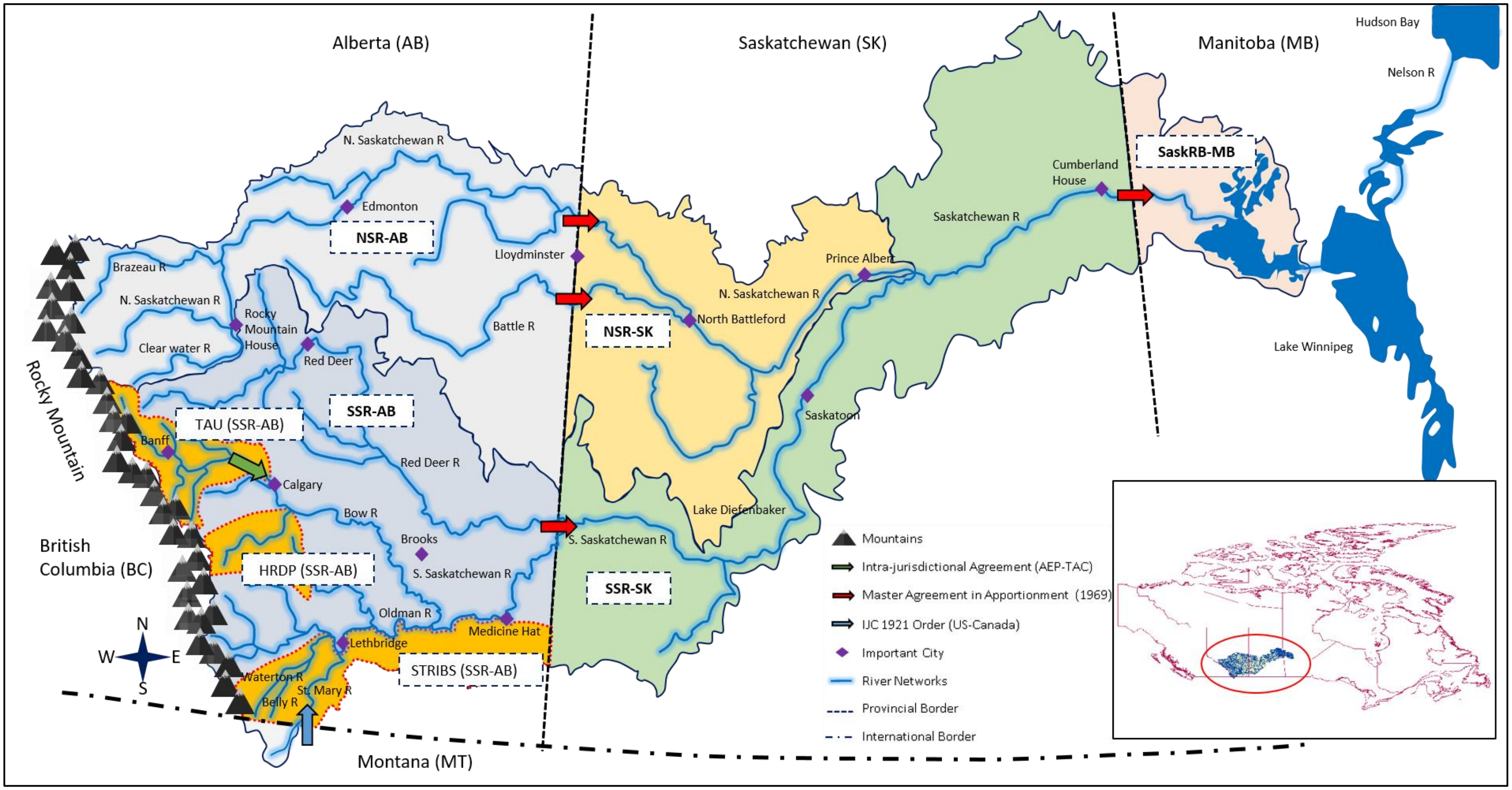


Figure 2.1 The Saskatchewan River Basin (SaskRB) showing the major tributaries (solid blue line), different water management areas (colored background), and water-sharing agreements (red, blue and light green arrow) from the Rocky Mountains, Alberta to the Lake Winnipeg, Manitoba

The spatial distribution of water demand in the SaskRB is not uniform, being most concentrated in the southern part of the basin, particularly in Alberta where the water abstraction reaches its allocation limit, and the provincial government has already restricted further allocation of water to new users (Alberta Environment, 2003a). Water demand in the NSR is moderate compared to the SSR, mostly related to the petroleum and other industries, and municipal demand. Water use in the SaskRB is mostly reliant on surface water, with only 2%–5% of water demand provided by groundwater, mostly for rural communities (Kulshreshtha *et al.*, 2012; Gonda, 2015; Prairie Provinces Water Board, 2017).

2.4 Water Management Modeling Challenges in the SaskRB

Implementing water management modeling for the SaskRB is relatively complex, not only because of the large spatial scale of the SaskRB but also because of the large number of water resources components and water user groups. To further illustrate this point, Figure 2.2 provides an overview of the water management modeling studies across the globe, similar in scope to the current study, focusing on the scale and water resources system components (mainly reservoirs) considered in the model development process. This review focused only on large complex water management modeling works to provide context for the level of modeling scale and physical system properties of the SaskRB. Compared to the most extensive and complex water management modeling works in the world such as California (Area (A) in km^2 =423970, Reservoir (R) =69) (California Department of Water Resources, 2017), Colorado (A=629367, R=90) (Sanvicente-Sánchez *et al.*, 2009), Connecticut (A=29000, R=73) (Julian *et al.*, 2016) water management projects in the US as well as other large river basins of the world; namely, Nile (A=3046334, R=14) (Digna *et al.*, 2017), Indus (A=1125000, R=2) (Stewart *et al.*, 2018), Mekong (A=773230, R=37) (Piman *et al.*, 2013), Ganga (A=860000, R=49) (Vat, 2018), Murray-Darling (A=1061469, R=46) (Dutta *et al.*, 2012), and South Platte (A=56980, R=67) (Colorado Water Conservation Board, 2017), the SaskRB is one of the largest and most complex river systems in the world in terms of scale (Area (A) in km^2 =405864) and reservoir operation (R=59).

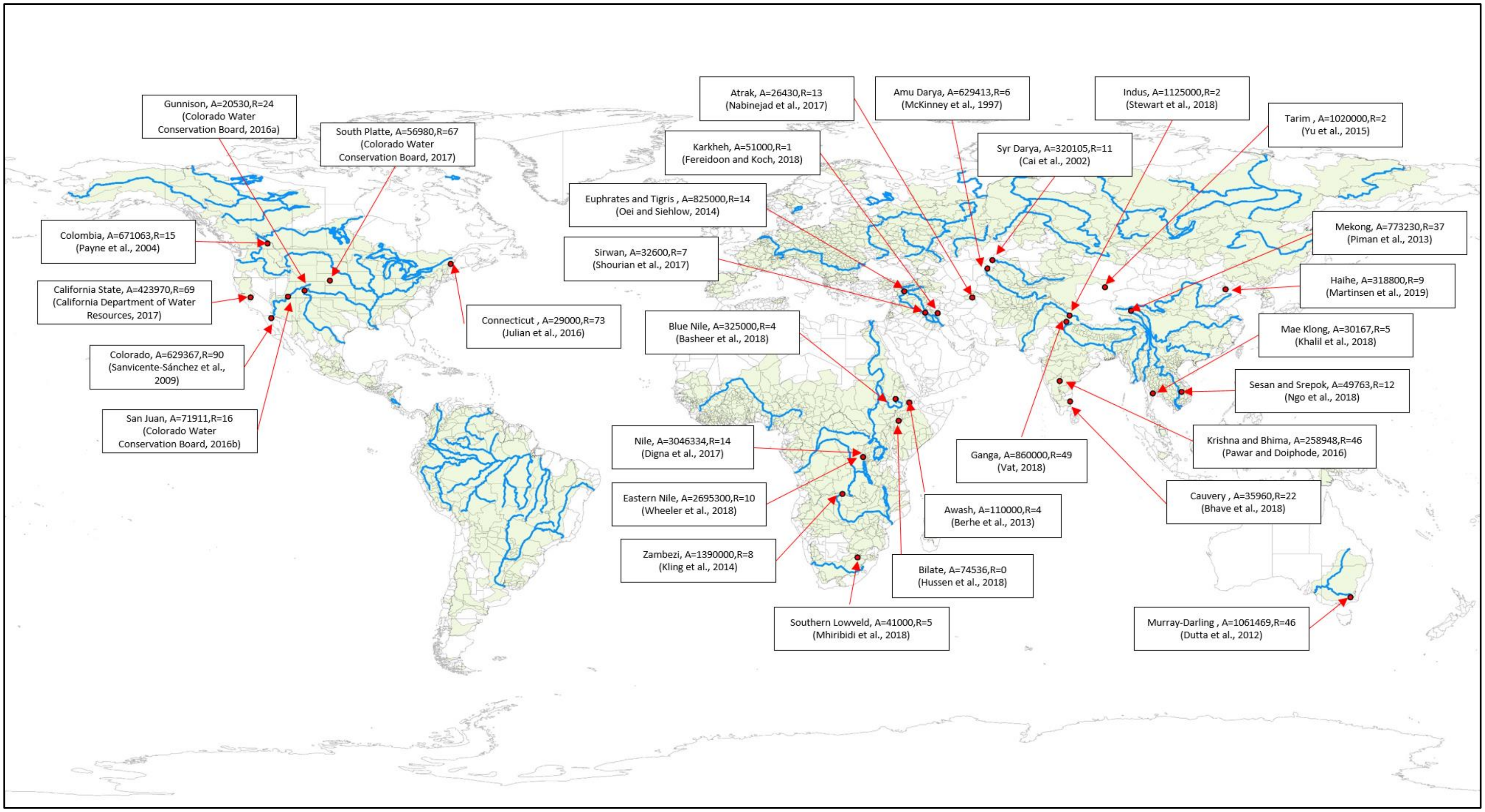


Figure 2.2 An overview of water management modeling studies in relation to the current modeling study, focusing on basin size and number of the reservoirs considered in model development [A is the basin area in km^2 and R is the number of reservoirs]. The solid black lines represent administrative borders, colored background areas represent major river basins, and solid blue lines represent major rivers of the world

A lack of a comprehensive database, which includes hydrological and climatological data as well as irrigation and non-irrigation demand, allocation, consumption, and return flow, is a major barrier for basin-scale water management modeling in the SaskRB. Also, data sharing privacy policy, particularly for privately-owned hydropower companies, is another challenge to water management modeling in this basin.

2.5 The Water Resources Modeling Platform

Currently, many generic software platforms are available for representing river basin operations to address water security challenges at the basin level. Some of the most widely-used of these models include MODSIM (Shafer and Labadie, 1978), the Water Evaluation and Planning (WEAP) System (Yates *et al.*, 2005), MIKE HYDRO Basin (DHI, 2003), the River Basin Simulation Model (RIBASIM) (Delft Hydraulics, 2006), OASIS (Hydrologics, 2009), RiverWare (Zagona *et al.*, 2001), and the Water Resource Integrated Modeling System (WRIMS) (Draper *et al.*, 2004). Overviews and comparisons of different decision support systems (DSSs) have been provided by Koch and Grünewald (2009), Teodosiu *et al.* (2009), Sechi and Sulis (2010), Sulis and Sechi (2013) and Zhang *et al.* (2013).

These models commonly use linear network flow programming and provide an integrated modeling environment via interactive linkages to multiple dimensions of water management (e.g., social, environmental, economic, groundwater, water quality, and others) for improved decision-making (Riepl, 2013). To develop a water management model for the SaskRB, this study utilized MODSIM DSS which is a network flow optimization-based river basin modeling environment, developed originally in 1978 at the Colorado State University (Shafer and Labadie, 1978) and has been evolving since then (Labadie and Larson, 2007).

MODSIM was selected because it can represent complex river systems and can resolve conflicts between competing stakeholders (Labadie, 1995). MODSIM is numerically efficient and stable (Morway *et al.*, 2016), and has been applied in a wide range of water-stressed areas globally demonstrating a good performance in water management modeling, planning, and policy analysis (Houk *et al.*, 2007; Ahn *et al.*, 2016; Chhuon *et al.*, 2016; Morway *et al.*, 2016; Shourian and Mousavi, 2017; Shourian *et al.*, 2017; F Emami and Koch, 2018; Fereidoon and Koch, 2018). MODSIM is the longest continuously-maintained river basin management software package currently available (Berhe *et al.*, 2013) and is well regarded relative to other river basin simulation packages (Winchester, 2008; Sulis and Sechi, 2013; Johnson, 2014). MODSIM customization option facilitates a low-level integration with other models, e.g., hydrologic (Ahn *et al.*, 2016; Vaghefi *et al.*, 2017; Fereidoon and Koch, 2018), economic (Farzad Emami and Koch, 2018), water quality (Dai and Labadie, 2002), groundwater (Morway *et al.*, 2016), and fish production (Campbell *et al.*, 2001) models.

The Water Resources Management Model (WRMM) is a surface water allocation model developed by Alberta Environment (2002) for water resources planning and management in the South Saskatchewan River Basin (SSRB) in Alberta. WRMM is a Linear Programming-based model that utilizes a penalty point system for water allocation to minimize an overall system penalty. The model can represent an extensive network of rivers, reservoirs, and diversions, several water use options, return flow from irrigation fields, hydropower production, and a variety of water allocation priorities. The full version of WRMM is not publicly available, and a limited version is accessible with permission from the Alberta Environment and Parks for non-commercial purposes. A details documentation and comparisons of different modeling platforms, including WRMM and MODSIM, are presented in Appendix A.

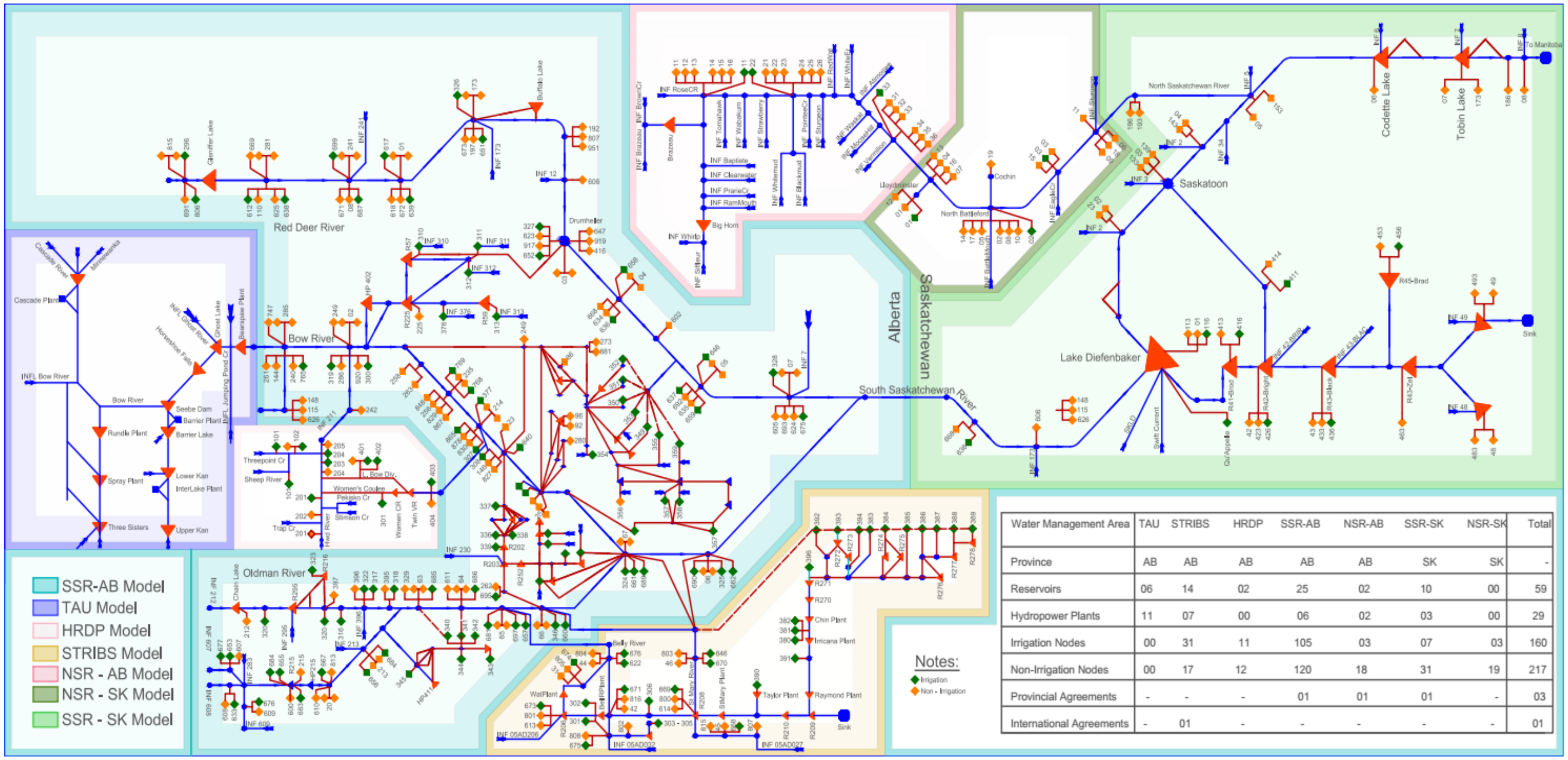
2.6 Model Development

Water resources management in the SaskRB is divided between several administrations with different operating policies, legislations, and modeling platforms, resulting in a multi-agency environment. The SaskRB can be divided into eight water management areas based on the regulatory administrations (AB, SK, and MB), sub-basin regions (NSR and SSR), and distinct operating policies for specially managed areas (TransAlta Utilities, Highwood River Diversion Plan, and Southern Tributaries). The AB portion of the SaskRB consists of five separate water management areas: (1) The SSR area (SSR-AB), (2) the NSR area (NSR-AB), (3) the TransAlta Utilities (TAU), (4) the Highwood River Diversion Plan (HRDP), and (5) the Southern Tributaries area (STRIBS). The SK portion of the SaskRB is divided into two water management areas, e.g., (6) the SSR area (SSR-SK), and (7) the NSR area (NSR-SK). The downstream portion of the SaskRB in MB (SaskRB-MB) is considerably less complicated than the other management areas of the basin. A separate water allocation model was not considered for this area, because there is no consumptive water demand currently in place, and only three run-of-the-river hydropower plants are in operation. The streamflow in the SaskRB-MB plays a vital role in the ecological and cultural values of several First Nation communities (Halliday, 2009). An overview of the various water management areas (same as the #1 to #7 indicated above) in the SaskRB is shown with different background colors in Figure 2.1 (geographically) and Figure 2.3 (schematic).

The present study developed a water allocation and management model for each management area (a “sub-model” of the full model). The temporal resolution of the developed sub-models was weekly for a simulation period of 91 years (1928-2018). To develop separate sub-models for different water management areas, this study gathered all information regarding hydro-meteorological data, reservoir characteristics and operating policies, water demands, return flows, environmental flow requirements, hydropower properties, channel (natural and diversion) properties, system priority ranking, and inter-jurisdictional as well as international water-sharing agreement details, and translated into the MODSIM framework.

A significant portion of the model system properties was guided by the existing WRMM setups, namely those for the SSR-AB and SSR-SK water management areas. Also, further information was collected from online resources of various administrations, including the TransAlta Corporation (TAC), AEP, WSA, and Alberta Utilities Commission (AUC), and Environment and Climate Change Canada's HYDAT and climate database. A brief description of water resources components of the SaskRB and collected system properties and associated sources are presented in Table 2.1 and Table 2.2, respectively. A details of data collection and model development processes were explained in Appendix B (SSR-AB and SSR-SK), Appendix C (TAU), Appendix D (HRDP), Appendix E (STRIBS), Appendix F (NSR-AB), and Appendix G (NSR-SK).

The MODSIM customization option was used to obtain an integrated water management model for the SaskRB (IWMSask) by running the sub-models in sequence from upstream to downstream, with the flow outputs of upstream models feeding into the flow inputs of downstream models (Figure 2.4). A summary of the sub-model integration process is documented in Appendix H. The developed IWMSask is a modeling platform that can represent the water management infrastructures of the SaskRB under current hydrologic and climate conditions.



Water Management Area	TAU	STRIBS	HRDP	SSR-AB	NSR-AB	SSR-SK	NSR-SK	Total
Province	AB	AB	AB	AB	AB	SK	SK	-
Reservoirs	06	14	02	25	02	10	00	59
Hydropower Plants	11	07	00	06	02	03	00	29
Irrigation Nodes	00	31	11	105	03	07	03	160
Non-Irrigation Nodes	00	17	12	120	18	31	19	217
Provincial Agreements	-	-	-	01	01	01	-	03
International Agreements	-	01	-	-	-	-	-	01

Figure 2.3 Schematic of the integrated water management model for the SaskRB (IWMSask). The background colors represent different water management areas of the SaskRB. There are 59 storage reservoirs, 29 hydropower plants, 160 irrigation and 217 non-irrigation nodes, one provincial and one international water-sharing agreements in the SaskRB. The natural channel, diversion channel, return flow channel, reservoir, irrigation demand, non-irrigation demand, junction, and system outflow are represented by the solid blue line, solid dark red line, dotted dark red line, dark orange triangle, light orange node, green node, blue circle, and blue octagon, respectively

Table 2.1 Water resource components of the SaskRB for different water management areas

Water Management Area	*TAU*	*STRIBS*	*HRDP*	*SSR-AB*	*NSR-AB*	*SSR-SK*	*NSR-SK*	*Total*
Province	AB	AB	AB	AB	AB	SK	SK	-
# Reservoir	06	14	02	25	02	10	00	59
# Hydropower Plant	11	07	00	06	02	03	00	29
# Irrigation Node	00	31	11	105	03	07	03	160
# Non-Irrigation Node	00	17	12	120	18	31	19	217
# Provincial Agreement	-	-	-	01	01	01	-	03
# Int. Agreement	-	01	-	-	-	-	-	01
Reference Appendix	C	E	D	B	F	B	G	-

Table 2.2 A summary of data sources considered in the sub-model development process for different water management areas of the SaskRB

Key Properties	*TAU*	*STRIBS*	*HRDP*	*SSR-AB*	*NSR-AB*	*SSR-SK*	*NSR-SK*
Inflow	BCD	BCD	BCD	ABCD	BCD	A	D
Water demand	L	C	BC	A	G	A	H
Reservoir	BCD	BCD	BCD	A	BD	A	-
Hydropower	EF	F	L	AF	EF	A	-
Channel	J	BJ	BJ	A	J	A	J
Environmental flow	J	BJ	BJ	A	J	A	J
Hydrometric	D	D	D	D	D	D	D
Hydro-meteorological	AC	AC	AC	AC	C	I	I
Operating policy	J	CJ	BK	A	J	A	HJ
Return flow	L	C	L	A	GJ	A	HJ
Agreement	B	B	L	A	B	A	L

Note: A= Water Resources Management Model (WRMM); B= Alberta Environment and Parks (AEP) online portal; C= South Saskatchewan River Basin (SSRB) Weekly Natural Flow Database; D= Environment Canada's HYDAT Database; E= TransAlta Corporation online portal; F= Alberta Utilities Commission (AUC) online portal; G= Current and future water use in Alberta (Alberta Environment, 2007); H= Water Security Agency of Saskatchewan (WSA) (Kulshreshtha, Nagy, *et al.*, 2012); I= Environmental Canada's Historical Climate Data; J= Based on approximation (details in reference appendix); K= Water Management Plan for the HRDP (Alberta Environment, 2008); L= Does not exist in the system.

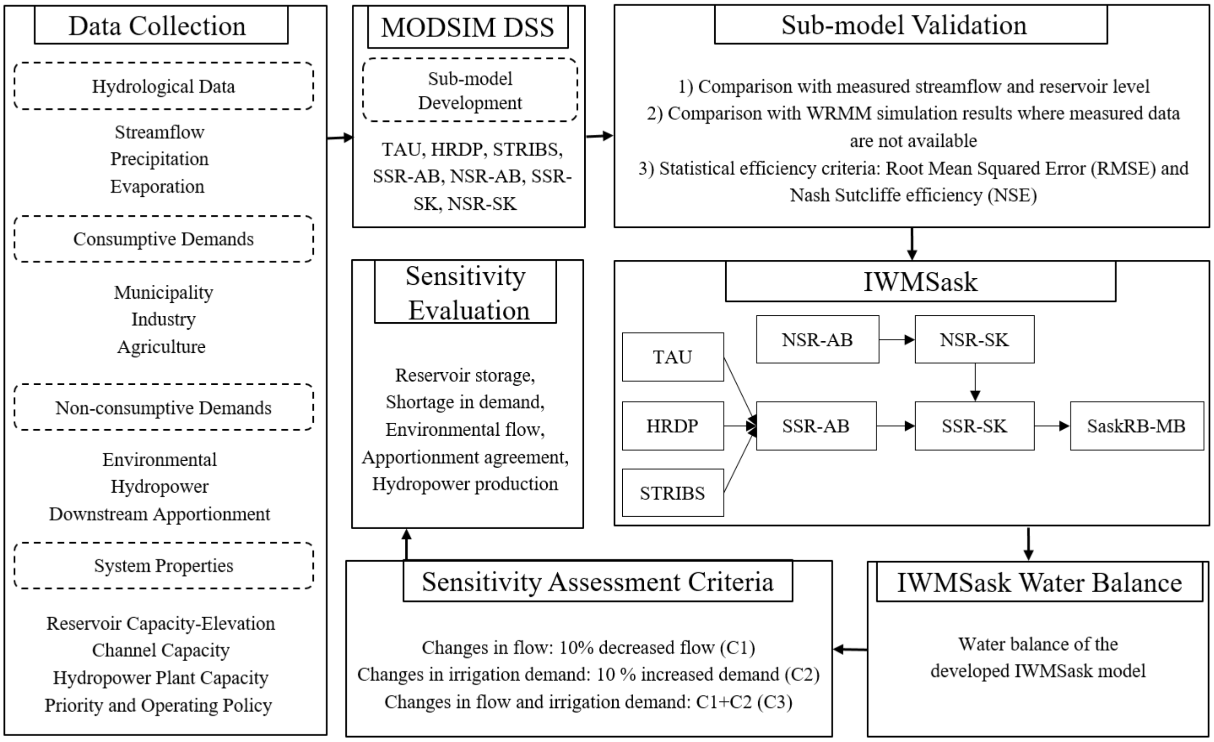


Figure 2.4 A flowchart of the present study, which describes the methodology of integrated water management model development and sensitivity assessment of the SaskRB water resources system under changing streamflow and irrigation demand conditions

The IWMSask can help decision-makers in water resources planning at sub-basin and basin-scale and can investigate possible water management options under future changing conditions. For instance, all demand points and reservoirs are expressed as nodes connected by links (natural or diversion channels), and the user can easily add new components (e.g., dam, diversion work, irrigation, or non-irrigation project) and investigate the impact of new infrastructure development on the entire system. Many complex water resources issues, e.g., environmental flow requirements, multiple operational zones, conditional operating policies in reservoirs, and short-term operation to long-term planning of the system, can easily be incorporated into the IWMSask platform. The user can change system properties (e.g., properties of inflow, demand, hydropower, reservoir, natural and diversion channel, water loss, return flow, simulation length, and time step, and the priority of different components) utilizing MODSIM graphical user interface without requiring any computer programing skills. The IWMSask can be coupled with hydrological, economic, groundwater, or water quality sub-models without re-programming and re-compiling the model source code. In addition, IWMSask can be a helpful tool to consider uncertainty in climate, hydrology, policy, and society in the process of water management and decision support by utilizing sensitivity and uncertainty analysis framework such as Variogram Analysis of Response Surface (VARS) (Razavi and Gupta, 2016a, 2016b; Razavi *et al.*, 2019). The IWMSask can also be used to improve reservoir operating policy or develop a new operating policy by coupling with a computationally efficient multi-objective optimization strategy as described by Asadzadeh *et al.* (2014) and Razavi *et al.* (2014).

2.7 Model Validation

A large number of water resource components have been modeled in the MODSIM environment, and showing the performance of all here is beyond the scope of this thesis. Some important points were selected across the SaskRB for assessing the model accuracy in simulating the current system. The performance was assessed with respect to the historical measured data and existing WRMM results. The historical data of reservoir level and streamflow, as well as allocation to different demand points, were not readily available for some regions, and WRMM simulation results were an alternative option to assess the credibility of the developed models. The reservoirs in the SaskRB were constructed for different time periods, mostly before 1990, and WRMM simulation results were available until 2001. Therefore, this study presented model performance results from 1991-2001 for comparison with observed data and WRMM simulation results. This validation strategy is also similar to that applied by other water management modeling efforts in this basin (Sheer *et al.*, 2013; Hassanzadeh *et al.*, 2014; Gonda, 2015; Safa, 2015; Sauchyn *et al.*, 2016).

Two most commonly used statistical performance criteria, i.e., the Root Mean Squared Error (RMSE) and Nash Sutcliffe efficiency (NSE), were used to assess the goodness of fit between MODSIM and historical data series, and the WRMM simulation results. The NSE ranges from $-\infty$ to 1; values closer to 1 indicate| sufficient quality of simulation results. According to Moriasi *et al.* (2007), water resources model performance can be categorized as ‘very good’ ($0.75<NSE\leq1.00$), good ($0.65<NSE\leq0.75$), satisfactory ($0.50<NSE\leq0.65$), and unsatisfactory ($NSE\leq0.50$). The RMSE shows the size of discrepancy in the simulation results with the same units of the constituent of interest, which aids in the analysis of the results.

To begin with, the North Saskatchewan River basin (NSRB), which is composed of NSR-AB and NSR-SK sub-models, was verified with respect to the observed streamflow at sub-model outlets (NSR near Deer Creek and NSR at Prince Albert), and reservoir level (Bighorn and Brazeau reservoirs) (Figure 2.5). Results show that developed NSR-AB and NSR-SK sub-model performance is very good (NSE>0.75), with a small discrepancy between simulated and measured data (Figure 2.5).

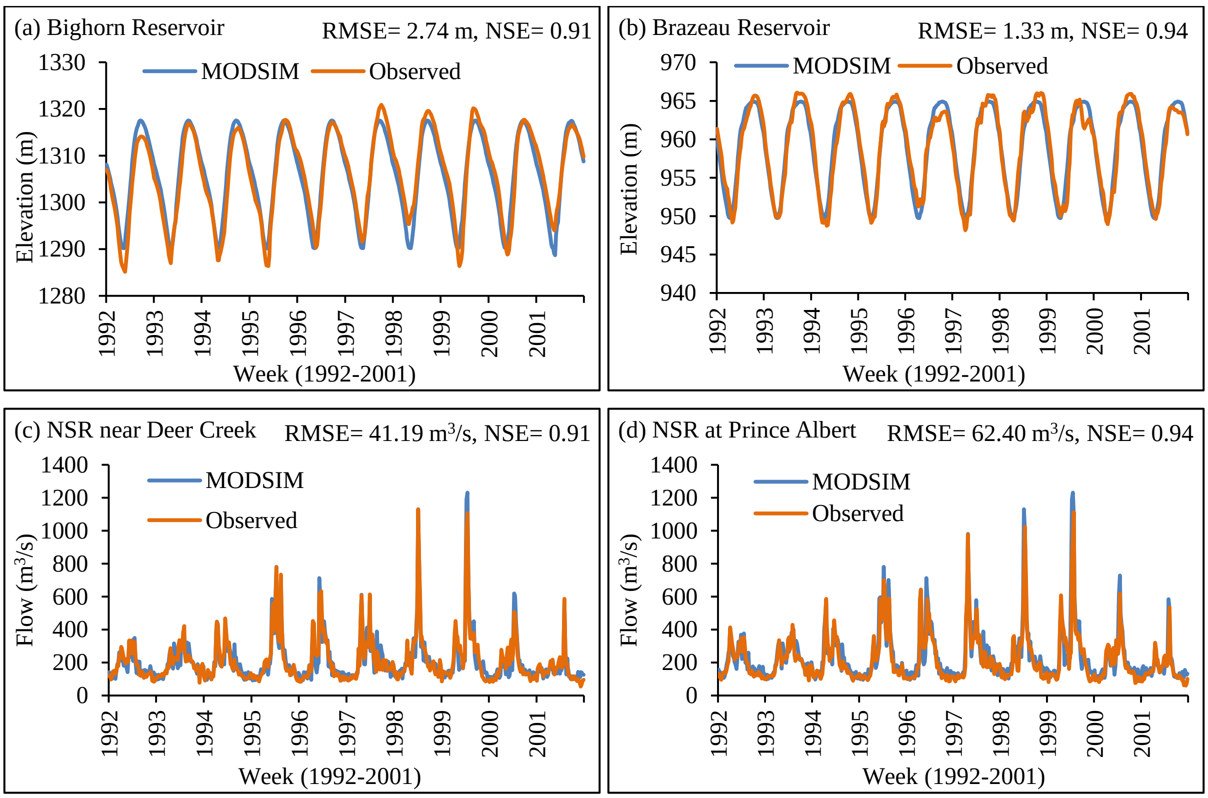


Figure 2.5 Weekly time series, comparing the NSRB reservoir elevation (a) Bighorn and (b) Brazeau reservoir, and streamflow (c) NSR near Deer Creek and (d) NSR at Prince Albert, against observed data for 1992-2001

The South Saskatchewan River basin in Alberta (SSRB-AB) is composed of four sub-models, i.e., TAU, STRIBS, HRDP, and SSR-AB. There is no consumptive water demand in the TAU, and a total of 11 hydropower power plants with six storage reservoirs are in operation, having a significant influence on downstream flow regime. The STRIBS and HRDP sub-models are particularly important for irrigation water diversion projects and control streamflow that feeds the downstream system, i.e., the SSR-AB sub-model. The SSR-AB sub-model covers a significant part of the basin and involves multi-sectoral water user groups, e.g., municipal, industrial, commercial, irrigation, recreation, and others.

For model verification, this study assessed the performance against the WRMM simulation results when the observed streamflow and reservoir level data were not readily available. Six important reservoirs, which involve Lake Minnewanka, Ghost, Oldman, Gleniffer Lake, Traverse, and Pine Coulee, were selected based on their importance in water management practice downstream. Also, streamflow at six important locations was considered to assess the model performance, which involves the Bow River below Ghost Dam, Highwood River near the Mouth, Belly River near the Mouth, Bow River near the Mouth, Red Deer River at Drumheller, and SSR at Alberta-Saskatchewan Border. The results are summarized in Figure 2.6 and Figure 2.7 for the reservoir elevation and streamflow, respectively. It is important to mention that the Oldman Reservoir was constructed in 1991, the operation was started in 1992, and it took a few years to reach full supply level (FSL), therefore, for the Oldman Reservoir, results are presented from 1994-2001 (Figure 2.6 (c)).

Figure 2.6 and Figure 2.7 show that developed sub-models (i.e., TAU, STRIBS, HRDP, and SSR-AB) performance is very good in emulating observed reservoir elevation and streamflow with higher NSE value (>0.75) and small discrepancy. The Ghost Reservoir operating policy, i.e., the rule curve, was not readily available, and this study deduced the rule curve based on the average of reservoir observed elevation. For this reason, the simulated Ghost Reservoir elevation cannot follow observed elevation exactly in some years, e.g., 1994, 1998, and 2000 (Figure 2.6 (b)). Therefore, the model performance in simulating the Ghost Reservoir elevation is good (NSE>0.65). Improving the Ghost Reservoir operation by adopting the actual operating policy could improve the simulation result performance. Apart from that, simulation results are also showing good consistency with WRMM results (Figure 2.6 (e) and (f), Figure 2.7 (a) and (c)).

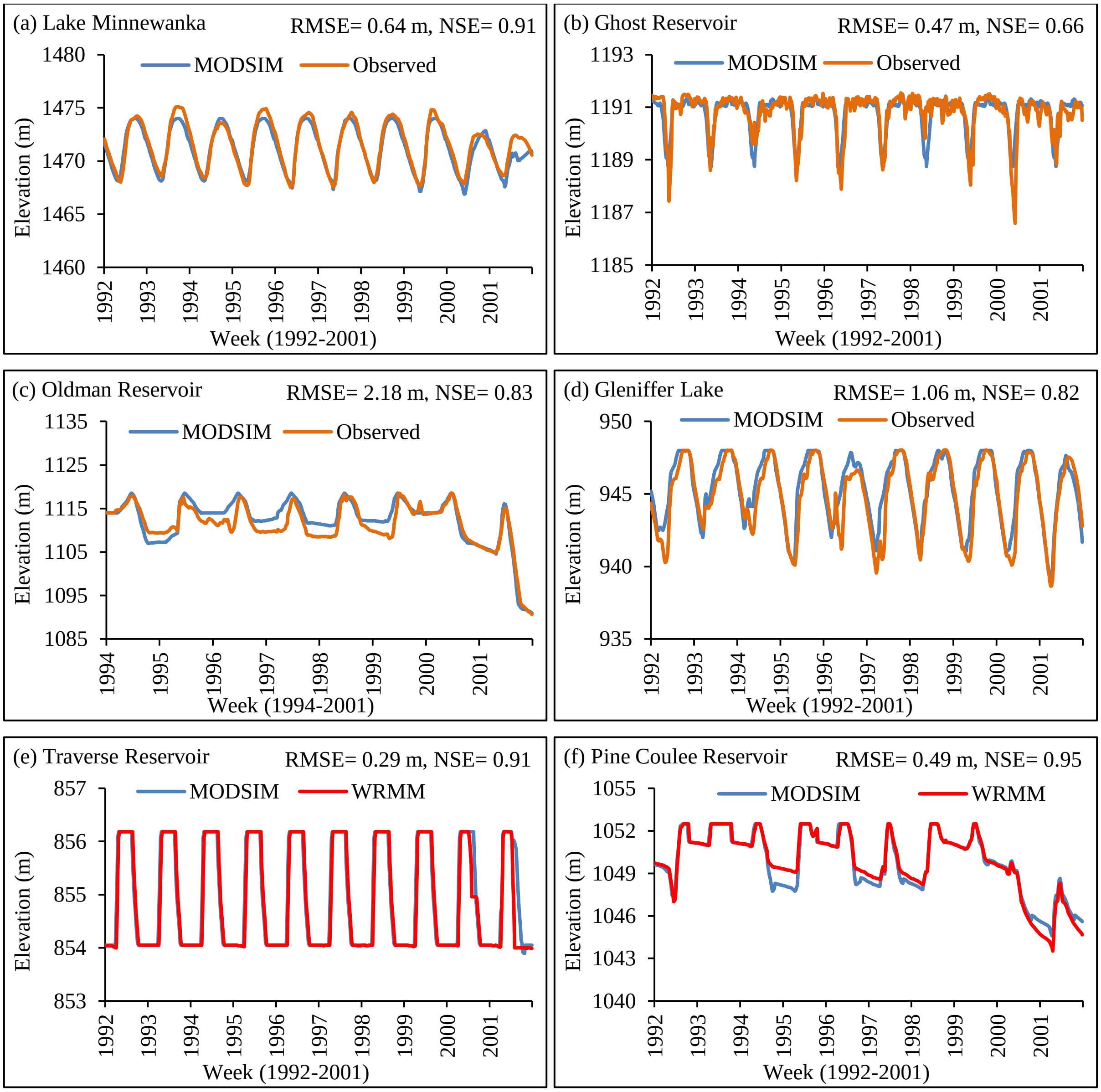


Figure 2.6 Weekly time series, comparing the elevation of (a) Lake Minnewanka, (b) Ghost (c) Oldman (d) Gleniffer Lake (e) Traverse, and (f) Pine Coulee reservoir against observed data and WRMM simulation results for 1992-2001

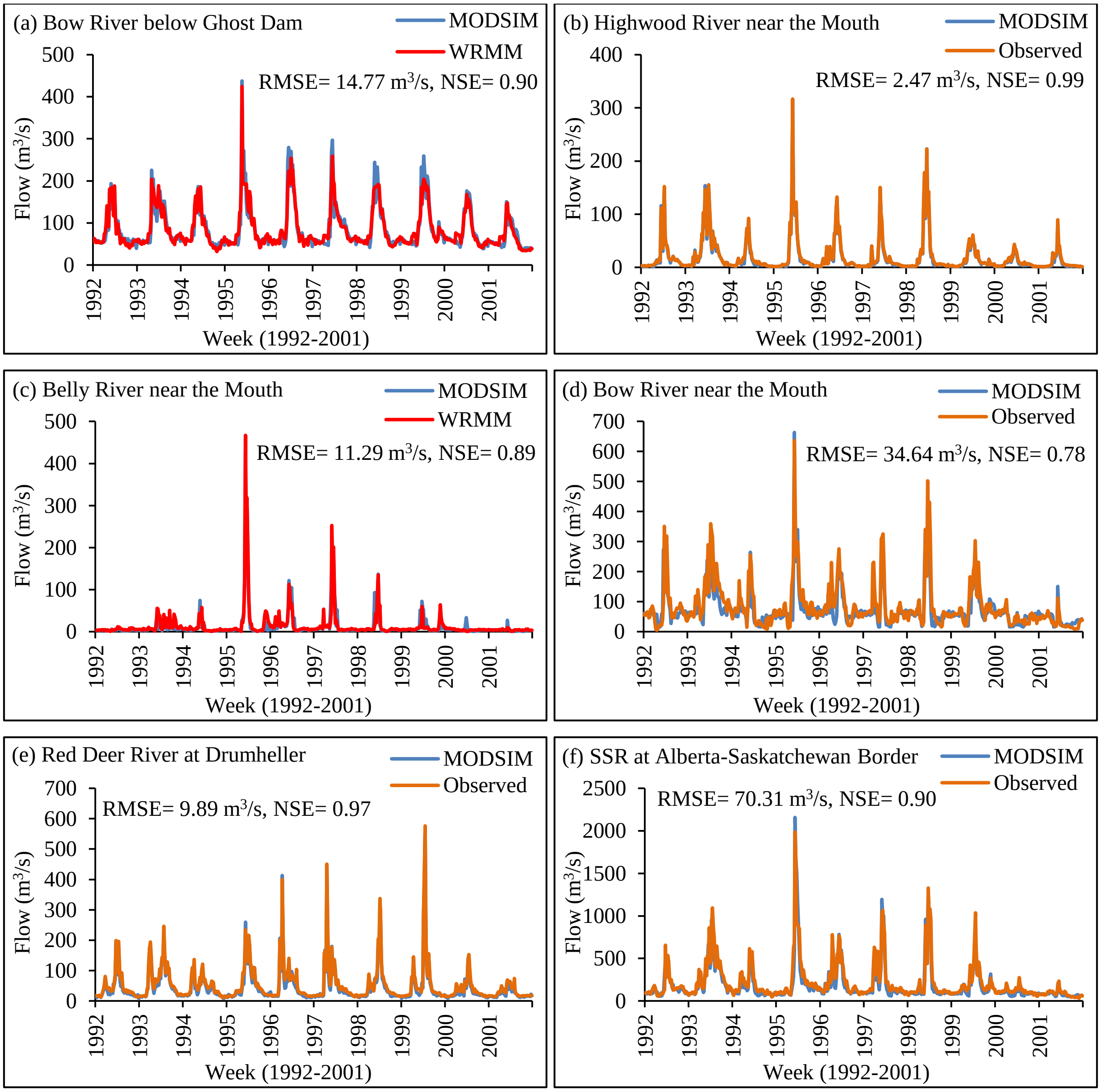


Figure 2.7 MODSIM simulated weekly time series of streamflow at six important locations in the SSRB-AB, compared with the observed data and WRMM simulation results for 1992-2001

MODSIM water allocation to irrigation, non-irrigation, and senior-most non-irrigation users (senior-most water license holders from municipal and domestic sectors) were compared with the available WRMM SSR-AB results, for ten years (1992-2001), to assess model consistency in water allocation (Figure 2.8). Figure 2.8 shows the empirical cumulative distribution function (ECDF) of total (sum of all nodes) weekly volume (in Million Cubic Meter (MCM)) of water allocated by MODSIM and WRMM to all irrigation (private and district irrigation) and non-irrigation users at sub-basin scale, in the Bow (a, e), Oldman (b, f), Red Deer (c, g), and SSR-AB (d, h) basins.

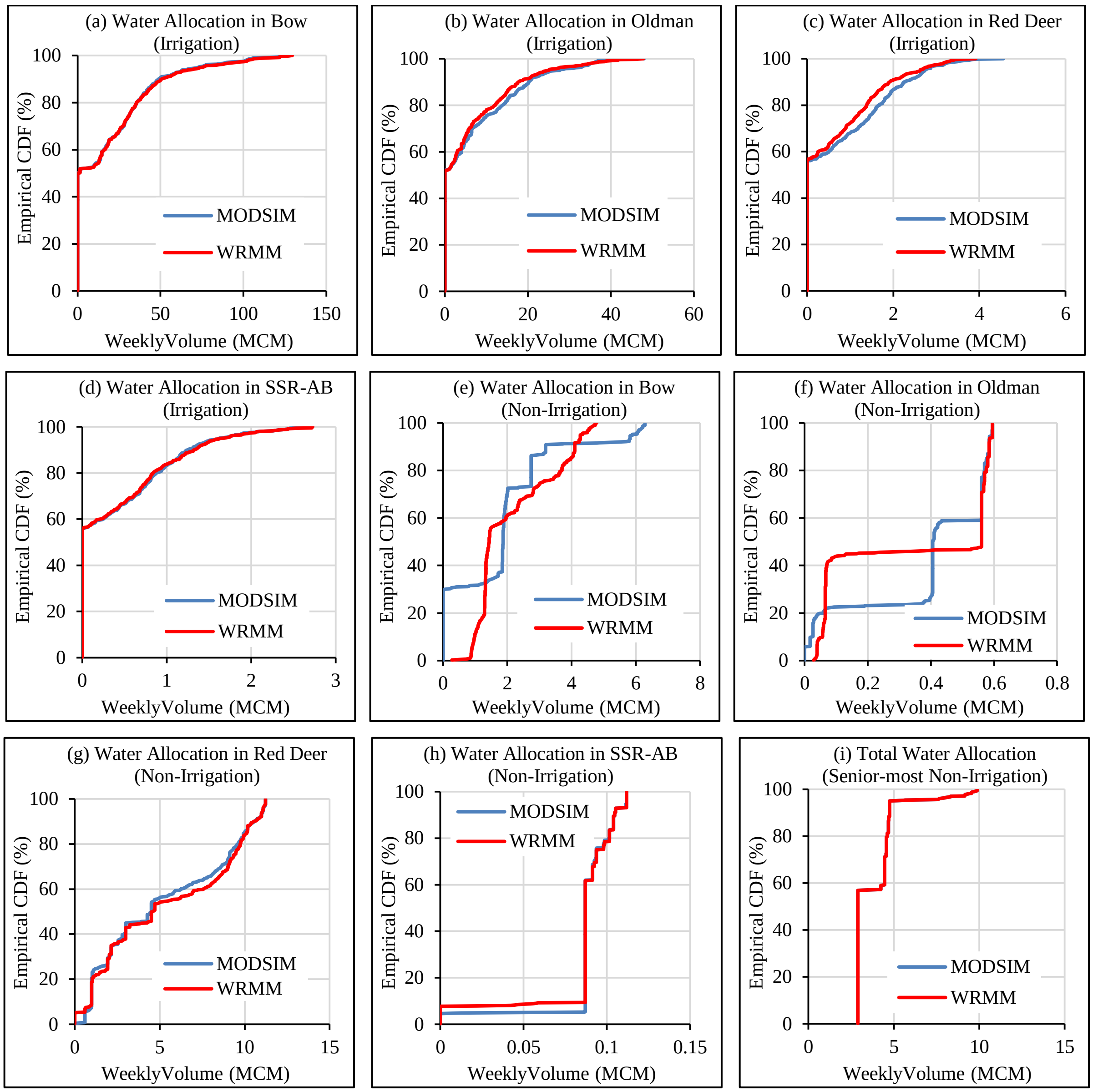


Figure 2.8 The empirical cumulative distribution function (ECDF) of weekly water allocation by MODSIM and WRMM, to irrigation nodes at Bow (a), Oldman (b), Red Deer (c), and SSR-AB (d) sub-basins, to non-irrigation nodes at Bow (e), Oldman (f), Red Deer (g), and SSR-AB (h) sub-basins, and total allocation to senior-most non-irrigation nodes (i) in the SSRB Alberta

Total water allocation to the senior-most non-irrigation users is also presented in Figure 2.8 (i). MODSIM is showing good consistency with WRMM results in terms of water allocation to irrigation, non-irrigation, and senior-most non-irrigation (Figure 2.8). However, there is a small difference in water allocation to non-irrigation users in the Bow and Oldman sub-basins (Figure 2.8 (e, f)).

The South Saskatchewan River basin in Saskatchewan (SSRB-SK) and the SaskR sub-basin in Saskatchewan were modeled in the SSR-SK sub-model. The Lake Diefenbaker Reservoir is the largest multipurpose water management structure in the SSR-SK sub-model. The outflow of the SSR-SK sub-model also represents the outflow of the entire SaskRB system. Therefore, this study assessed the SSR-SK model performance with respect to the Lake Diefenbaker elevation (Figure 2.9 (a)), and streamflow at two important locations downstream of the Lake Diefenbaker Reservoir, e.g., SSR at Saskatoon (Figure 2.9 (b)) and the SaskR flow below Tobin Lake (Figure 2.9 (c)). MODSIM simulation results show very good performance compared to the observed reservoir elevation (NSE>0.75). Apart from some outliers, the very small discrepancy between the simulated and observed SSR flow at Saskatoon and SaskR flow below Tobin Lake also shows a very good performance.

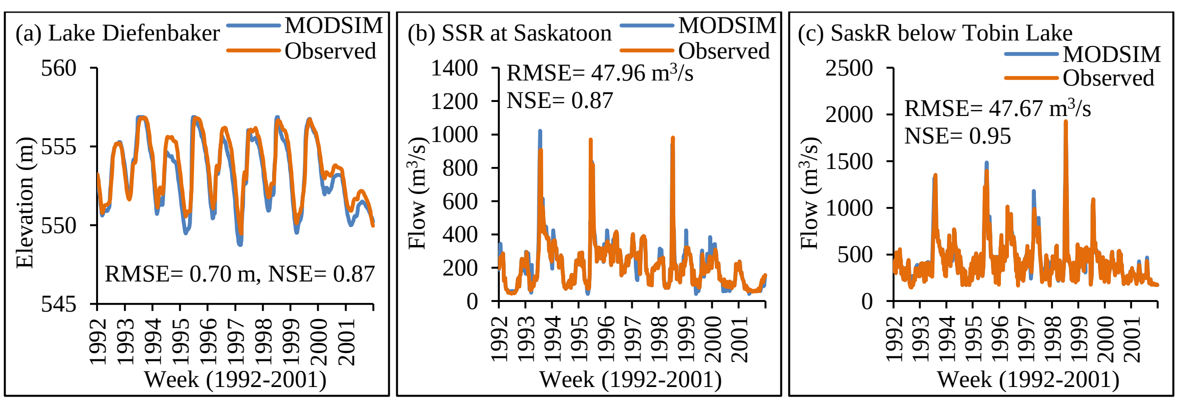


Figure 2.9 MODSIM simulated weekly times series for important components of the SSR-SK sub-model comparing with the observed data from 1992-2001

The performance of the IWMSask was also assessed by checking the water balance of the entire system in the model estimations. To explain further, total available water (inflow from rivers, reservoir precipitation, return flow to the system (unused water), and reservoir storage gain over the simulation period) and total outflow (outflow to downstream, reservoir evaporation, reservoir storage loss over the simulation period, and allocated water to demand points) were estimated (in Million Cubic Meter (MCM)) at sub-basin scale, for NSR basin (NSRB), SSR basin in AB (SSRB-AB) and SSR basin in SK (SSRB-SK), and summarized by taking annual mean to check the mass balance of the system (Table 2.3). The water balance of the entire system shows a good result as the modeling error is less than 0.5%, which depicts that there was no artificial gain or loss in the model's calculation process. However, the small modeling error could be generated due to the round-off error in the calculation process as the system contains many water resource components.

Table 2.3 Water balance of the developed integrated water management model for the SaskRB (IWMSask) for the period of 1991-2001

Category	*NSRB*	*SSRB-AB*	*SSRB-SK*
Inflow from rivers (MCM)	156.24	182.47	334.74
Outflow to downstream (MCM)	151.17	111.61	322.69
Allocation to demand (MCM)	6.24	71.00	6.22
Reservoir storage gain (+) / loss (-) (MCM)	0.01	-0.13	-0.13
Reservoir evaporation (MCM)	0.39	5.33	7.91
Reservoir precipitation (MCM)	0.24	1.45	1.21
Return flow to the system (MCM)	1.36	4.97	0.81
Total available water (MCM)	157.83	188.89	336.76
Total outflow (MCM)	157.80	188.07	336.95
Difference (MCM) *(Total available water- Total outflow)*	0.03	0.82	-0.19
Modeling Error (%) *(Difference/ Total available water)*	0.02%	0.44%	-0.06%

2.8 Sensitivity Assessment of the SaskRB Water Resources System

The irrigation and non-irrigation water uses, and ecosystem health in the SaskRB greatly depend on the streamflow, and any changes in the streamflow properties can increase the vulnerability of the downstream water resources system (Nazemi and Wheater, 2014). Canada has experienced an increase in temperature but a decrease in precipitation (DeBeer *et al.*, 2016). For instance, Hao *et al.* (2013) showed that the monthly warm/dry extremes (high temperature and low precipitation) had increased substantially in 1978-2004 relative to 1951-1977. Also, Zhang *et al.* (2000) found that the mean annual temperature in southern Canada has increased by 0.5 to 1.5 °C, while the precipitation showed a significant negative trend during the spring season. These changes in temperature and precipitation behavior can increase irrigation demand and change river flows. For example, Pomeroy *et al.* (2009) and North Saskatchewan Watershed Alliance (2008) showed that climate change-induced hydrological variability in the upstream of the SaskRB can reduce the SSR and NSR flows by 8.5% and 5% at the Alberta/Saskatchewan border, respectively. On the other hand, the rapid growth of the population and the development of new infrastructure can increase irrigation demand in this region. For instance, in Alberta, the Oldman and Bow river sub-basins have a room of 10% and 20% irrigation expansion within the limit of the SSRB regulation plan (Alberta Environment, 2003b). The downstream Saskatchewan province also has a potential of 400% irrigation expansion over the next 40 years (Hassanzadeh *et al.*, 2014).

To represent the changes of streamflow and irrigation demand which may arise due to climate change and infrastructure development in future, the present study considered three different changing conditions, which involve a decreased streamflow by 10% (C1), an increased irrigation demand by 10% (C2), and a combination of C1 and C2 (C3). The IWMSask was used to assess the sensitivity of the SaskRB water resources system, under these three changing conditions (e.g., C1, C2, and C3). The IWMSask, when representing the system under current streamflow and demand conditions, is referred to as the “Base Model (C0)”. The sensitivity of the SaskRB water resources system was assessed under five categories, such as changes in reservoir storage, hydropower production, shortage in irrigation and non-irrigation supply, and the viability of transboundary apportionment agreement and environmental flow requirements. The analysis was performed at the sub-basin scale to identify the vulnerable regions and sectors to such changes.

2.8.1 The Sensitivity of Reservoir Storage

In the SaskRB, there are 59 reservoirs in operation to support different water uses and to provide protection against extreme hydrological conditions (e.g., drought and flood). Therefore, it is vital to analyze the sensitivity of the reservoir storage under changing supply or demand conditions. Figure 2.10 and Figure 2.11 represent the sensitivity of reservoir mean weekly and annual storage (in MCM), respectively, under different demand and supply conditions for various sub-basins of the SaskRB. The reservoirs of the southern part of the basin (SSRB), which is already in water-stressed condition, are very sensitive to the changes in streamflow (C1), irrigation demand (C2), or combination of both (C3) (Figure 2.10 (a)-(e) and Figure 2.11). In the northern part of the SaskRB (NSRB), reservoir storage changes are minimal (Figure 2.10 (f) and Figure 2.11).

Results show that reservoir storage in Bow, Oldman, SSR-SK, and SaskR sub-basins are sensitive to both streamflow and irrigation demand changes, while in Red Deer sub-basin, reservoir storage is only sensitive to the changes in streamflow. The reservoir storage in Oldman, SSR-SK, and SaskR sub-basins are affected higher than other sub-basins of the SaskRB due to C1, C2, and C3 cases. The reservoirs are mainly used for flow regulation in Red Deer, for irrigation and hydropower in Bow, for flow regulation and irrigation in Oldman, for irrigation and hydropower in SSR, and for flow regulation and hydropower in SaskR sub-basins. These changes in reservoir storage would negatively impact recreational boating, hydropower production, and would increase the difficulties and cost of pumping water for various uses such as irrigation.

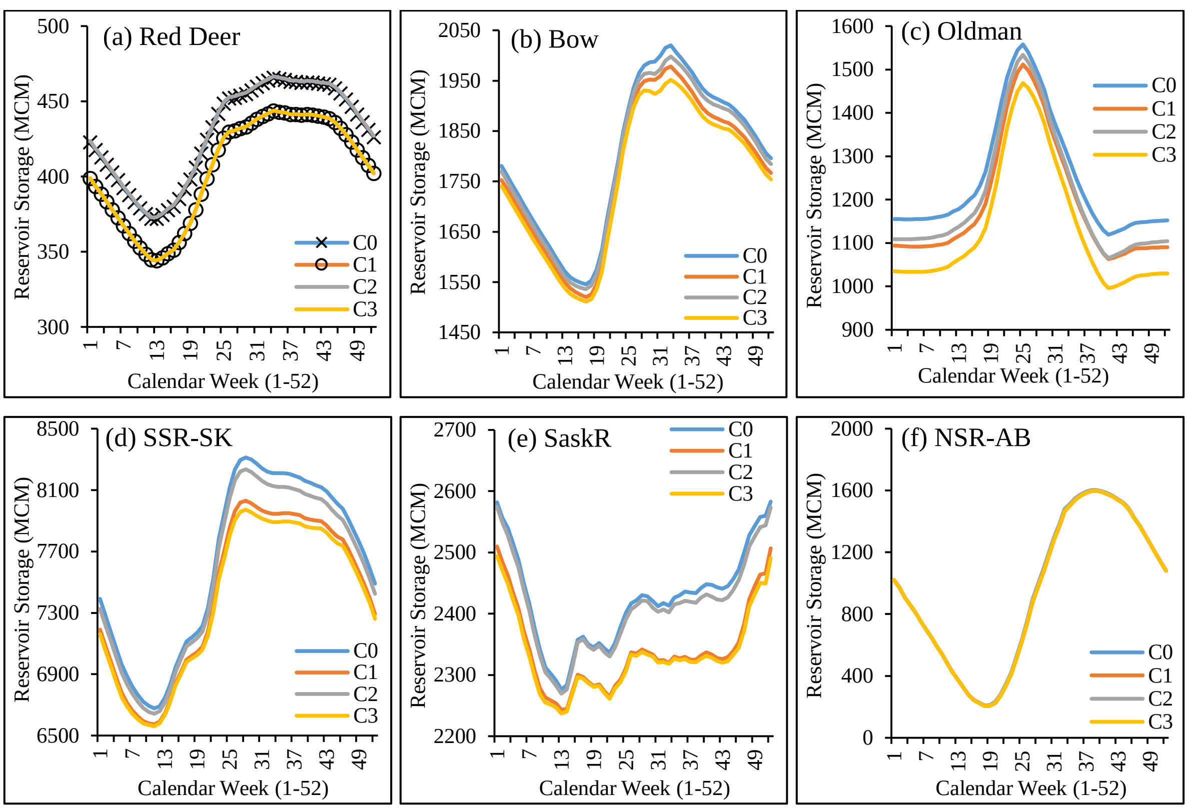


Figure 2.10 The sensitivity of reservoir mean weekly storage at different sub-basins of the SaskRB

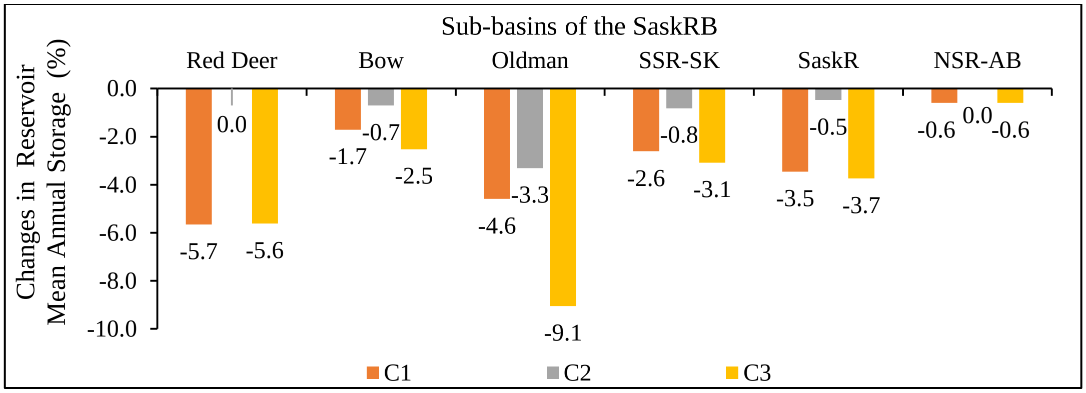


Figure 2.11 Changes in reservoir mean annual storage at different sub-basins of the SaskRB, under decreased streamflow (C1), increased irrigation demand (C2), and a combination of both (C3)

2.8.2 The Sensitivity of Irrigation and Non-irrigation Shortage

The simulation results in terms of annual shortage in irrigation at important sub-basins, e.g., Red Deer, Bow, Oldman, and SSR-AB, are plotted in Figure 2.12 by showing empirical cumulative distribution function (ECDF) of annual shortage volume (in Million Cubic Meter (MCM)) from 1928-2018, for different sensitivity cases, e.g., C1, C2, and C3. Table 2.4 further depicts the changes in mean annual irrigation and non-irrigation shortage (in MCM) for all sub-basins of the SaskRB. Table 2.4 was prepared to reflect the relative shortage (shortage with respect to the Base Model (C0)) of different sub-basins due to three sensitivity cases. It is important to mention that there is no irrigation demand currently in place in the SaskR sub-basin, and therefore no data is presented in Table 2.4 for the SaskR sub-basin.

Results show that changes in streamflow (C1), irrigation demand (C2), and changes as in C3 increase annual irrigation shortage in all sub-basins (Figure 2.12). However, the NSR-AB and NSR-SK show no irrigation shortage under any of these changes (Table 2.4). The sensitivity of annual irrigation shortage for all three changing conditions is higher in Bow, followed by Oldman (Table 2.4). Irrigation shortage in SSR-SK sub-basin increases only due to the increased irrigation demand (C2). The sensitivity of annual non-irrigation shortage is higher in Bow, followed by Red Deer, Oldman, SSR-AB sub-basins (Table 2.4).

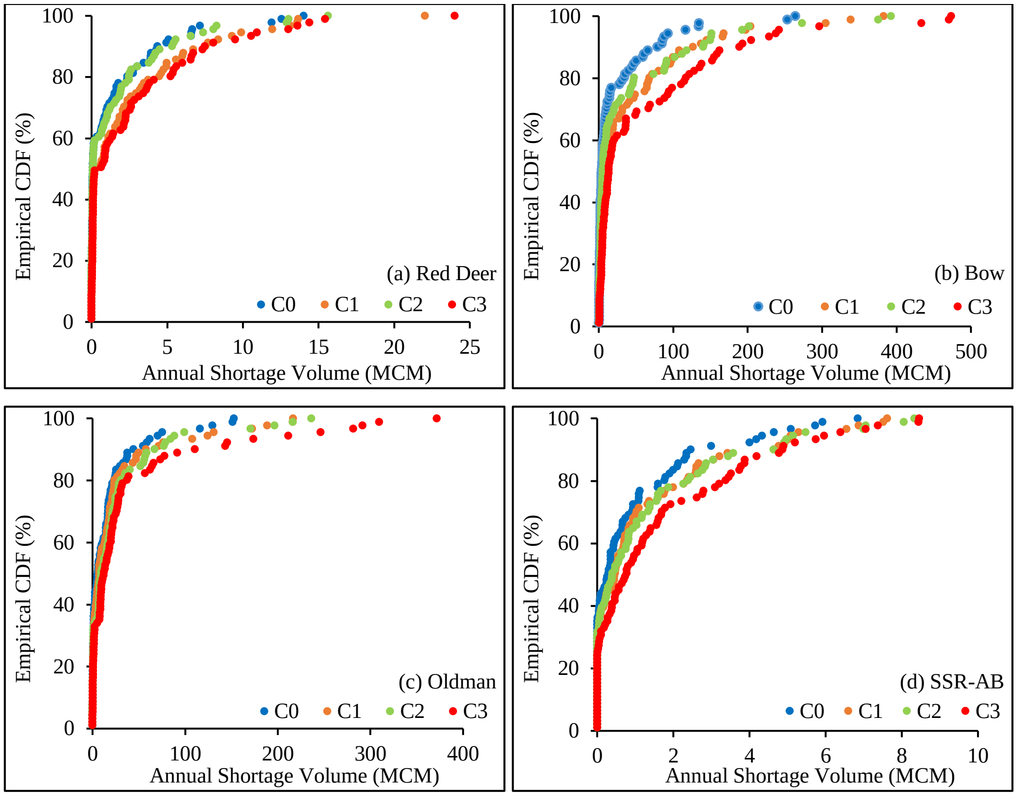


Figure 2.12 The empirical cumulative distribution function (ECDF) of annual irrigation shortage at important sub-basins of the SaskRB under different changing conditions

Table 2.4 The relative changes of mean annual irrigation and non-irrigation shortage at different sub-basins of the SaskRB

Sub-Basin	Irrigation Shortage (MCM)				Non-irrigation Shortage (MCM)			
	Shortage	Relative Shortage			Shortage	Relative Shortage		
	C0	C1	C2	C3	C0	C1	C2	C3
Red Deer	1.46	0.92	0.15	1.19	62.07	13.53	0.31	13.83
Bow	23.11	19.55	16.12	40.12	122.04	17.64	3.91	22.04
Oldman	17.63	6.46	8.42	21.94	11.09	2.58	1.83	4.71
SSR-AB	0.94	0.31	0.36	0.70	0.19	0.06	0.04	0.11
NSR-AB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NSR-SK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SSR-SK	369.65	0.00	36.97	36.97	118.12	0.00	0.00	0.00
SaskR	-	-	-	-	14.11	0.00	0.00	0.00

2.8.3 The Sensitivity of Environmental Flow Requirements (EFRs)

The Environmental Flow Requirements (EFRs) involve two different categories of streamflow needs, i.e., “Instream Objectives” (IO) and “Instream Flow Need” (IFN) (Alberta Environment, 2006). The IO is the minimum flow requirement of the river to keep the system active, and water withdrawal is not permitted below IO. The IFN is the flow requirements to protect the aquatic environment. The IO receives maximum priority, followed by IFN in the water management strategy of the SaskRB. The empirical cumulative distribution functions (ECDF) of weekly flows from 1928-2018 for four major rivers at environmentally important locations are presented in Figure 2.13. Table 2.5 further summarizes the number of weeks when simulation results violate the IO and IFN. Results show that IO was satisfied all the time period (as it receives maximum priority), while small violations were found for IFN in all reaches, which is negligible compared to the entire simulation period (1928-2018, 91 years, 4,732 weeks) (Table 2.5).

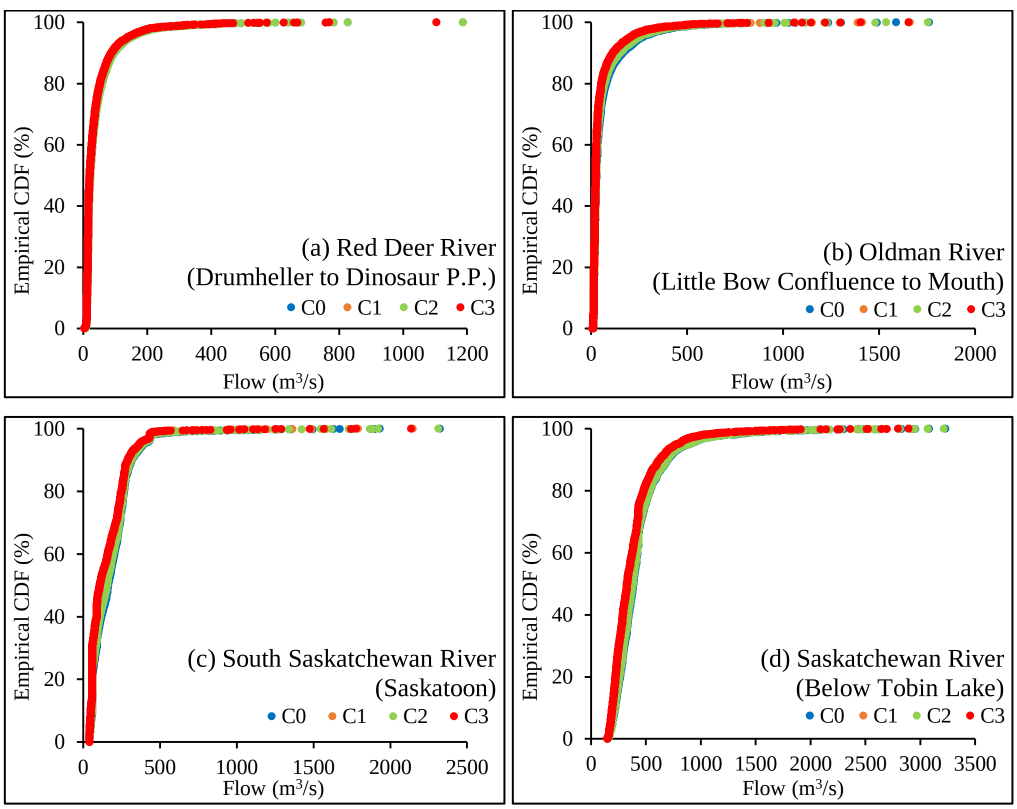


Figure 2.13 The empirical cumulative distribution function (ECDF) of weekly flows for four major rivers at environmentally important locations in the SaskRB under different changing conditions

Table 2.5 The number of weekly time steps from 1928-2018 when the system violated minimum streamflow requirements (MSR) under different changing conditions

Reach Name	Flow Type	C0	C1	C2	C3
Red Deer River (Drumheller to Dinosaur P.P.)	IO	0	0	0	0
	IFN	146	204	140	217
South Saskatchewan River (Saskatoon)	IO	0	0	0	0
	IFN	106	219	133	241
Saskatchewan River (Below Tobin Lake)	IO	0	0	0	0
	IFN	34	70	35	74
Bow River (Below Bassano Dam)	IO	0	0	0	0
	IFN	96	102	101	104

2.8.4 The Sensitivity of the Transboundary Apportionment Agreement

According to the Master Agreement on Apportionment (1969), the upstream province will deliver 50% of the annual volume of natural flow that it receives at the provincial border to the downstream province. The annual volume of natural flow is the sum of total annual local flows and total annual natural inflows coming from the upstream part of the basin to the provincial border. The apportioned flow (%) is the amount of annual flow volume at the provincial border that moves toward the downstream province. The value of apportioned flow needs to be equal to or greater than 50%. To investigate the viability of apportionment commitment, this study presented IWMSask simulated streamflow for three major transboundary rivers of the SaskRB (e.g., SSR, NSR, and SaskR) and for all experimental cases (i.e., C1, C2, and C3) in Figure 2.14 (a)-(c). Figure 2.14 (d) represents the changes in the mean annual transboundary river flow at the provincial border due to the changes described by C1, C2, and C3.

Results show that the NSR and SaskR can meet the apportionment commitment all years (1928-2018). However, the SSR under the baseline condition, violated the commitment in 5 years, and changes in streamflow and irrigation demand as in C1, C2, and C3, the number increased considerably, e.g., C1 (6), C2 (8), and C3 (13), which could be an issue of concern under changing demand and supply in future (Figure 2.14 (a)-(c)). The mean annual discharge of the SSR reduced by 12%, 3%, and 15% for C1, C2, and C3, respectively (Figure 2.14 (d)). Therefore, unlike other transboundary rivers of the SaskRB, the SSR flow was found to be very sensitive to a 10% decrease in streamflow (C1), a 10% increase in irrigation demand (C2), and combination of C1 and C2 (C3).

The flow of the NSR is reduced by 10% due to the changes of streamflow in C1, and SaskR flow is reduced by 11% and 12% due to C1 and C3, respectively.

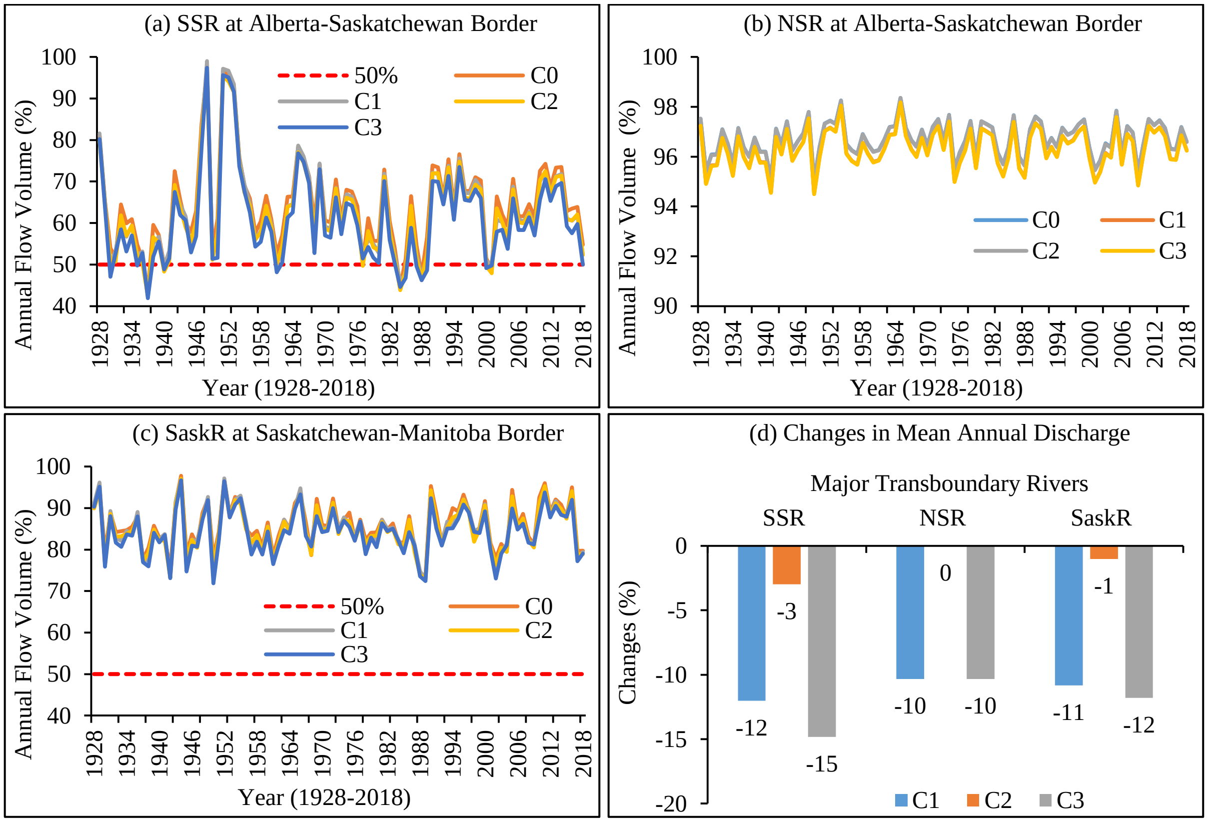


Figure 2.14 Percentage of annual streamflow volume with respect to the naturalized flow volume at the provincial border for three major transboundary rivers of the SaskRB, i.e., SSR (a), NSR (b), and SaskR (c), which are subject to satisfy 50% apportionment on an annual basis, under the Master Agreement on Apportionment (1969), (d) changes in mean annual discharge of major transboundary rivers of the SaskRB

2.8.5 The Sensitivity of the Hydropower Production

The sensitivity of hydropower at the sub-basin scale was also analyzed to assess hydropower vulnerability to changing streamflow and irrigation demand conditions. Figure 2.15 presents the relative changes (changes with respect to the Base Model (C0)) of average hydropower for different sub-basins of the SaskRB. Results show that 10% decreased streamflow (C1) reduced hydropower in all sub-basins, 10% increased irrigation demand (C2) reduced hydropower only in SSR-SK and SaskR sub-basins, and combination of both cases (C3) reduced hydropower in all sub-basins except Oldman where a small increase of hydropower is found (Figure 2.15 (a)). Figure 2.15 (a) also shows that the hydropower increased in Bow and Oldman sub-basins due to a 10% increased irrigation demand (C2).

The hydropower increased by 1-4 % in the Bow and Oldman sub-basins (Figure 2.15 (b)), since all the hydropower plants located in the Oldman and downstream of Bow sub-basins are run-of-the-river system and utilizes irrigation water supply for power generation. The increased irrigation demand in C2 also increased water supply to different irrigation users, which is the main reason for this small increase in hydropower generation. The average hydropower is reduced by 18%, 8%, 9%, 16%, and 12% in Red Deer, Bow, NSR-AB, SSR-SK, and SaskR sub-basins, respectively which might create difficulties to meet energy demand in future under reduced streamflow coupled with increased demand condition. It is important to note that in the downstream part of the SaskRB in MB (SaskRB-MB), Manitoba Hydro, a provincial Crown Corporation, uses the flow of SaskR for hydropower production, which were not included in this study.

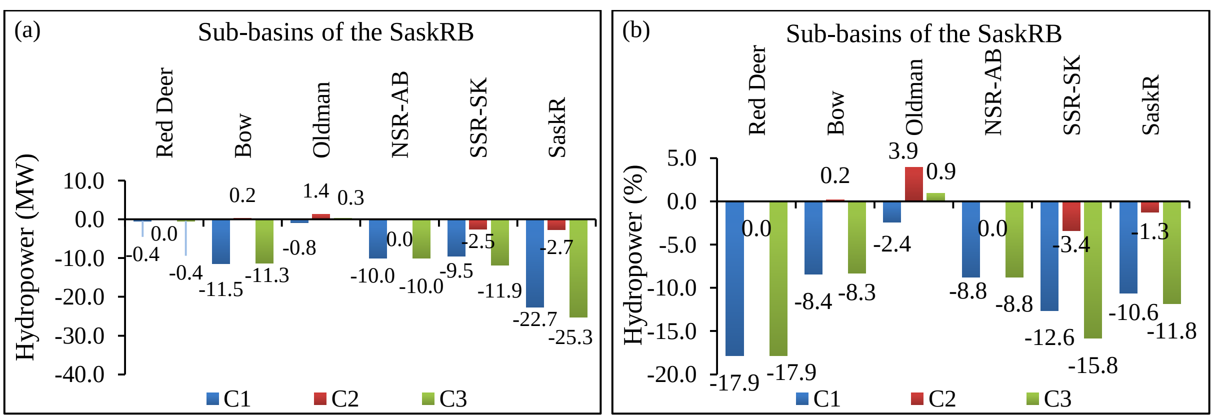


Figure 2.15 The sensitivity of hydropower production at different sub-basins of the SaskRB under changing streamflow and irrigation demand conditions

2.9 Conclusion

A total of seven water allocation sub-models were developed for different water management areas of the SaskRB, based on the current water management infrastructure. All sub-models were integrated to develop IWMSask that can simulate water allocation from the Rocky Mountains in the upstream to the downstream SRD. The validation results of all the sub-models show a good representation of the current water management system, and the water balance of the IWMSask shows less than 0.5% error in simulation results for the entire simulation period (1928-2018). The sensitivity of different system components of the SaskRB was assessed using the IWMSask under changing streamflow and irrigation demand conditions. Results show that reduced streamflow together with increased irrigation demand would (1) reduce reservoir storage, particularly in the Bow, Oldman, SSR-SK and SaskR sub-basins, (2) increase annual irrigation shortage in Bow followed by Oldman, SSR-SK, and Red Deer sub-basins, and non-irrigation shortage in Bow followed by Red Deer and Oldman sub-basins, (3) satisfy minimum streamflow requirements at environmentally important locations due to their higher priority in the operating policy, (4) increase the number of years when apportionment agreement is violated in the SSR, and (5) reduce average hydropower production in the Red Deer, Bow, NSR-AB, SSR-SK, and SaskR sub-basins. The changes in reservoir storage would create difficulties for recreational boating and pumping water for various uses such as irrigation. The reduction in hydropower production, especially in the upstream of Bow sub-basin and downstream of the SSR and SaskR sub-basins, might create stressful conditions to meet the energy requirement of this region.

The developed sub-models can be used in local water management planning, and the IWMSask can be a helpful tool in long-term basin-level policy analysis and decision making. Besides, the IWMSask can create new opportunities for the decision-makers and researchers to analyze and investigate many water security concerns at basin-level by considering uncertainties in supply and demand due to the natural and anthropogenic activities, and by incorporating IWMSask with other dimensions of sustainability, e.g., social, economic, and the environment. To conclude, IWMSask is an important first step towards integrated basin-scale water management and planning in the SaskRB and will be helpful to different stakeholders as well as decision-makers for the analysis of trade-offs between resource allocation and economic, social, and environmental benefits.

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3 Chapter 03: Conclusion

3.1 Summary of the Study

The SaskRB is a large transboundary river system in western Canada and transcends three Canadian provinces (Alberta, Saskatchewan, and Manitoba) and one US state (Montana). Water resources management in the SaskRB is fragmented because of political boundaries, and the provincial administrations are responsible for water management planning and decision making within each province. The transboundary water resources are managed by the Master Agreement on Apportionment-1969 and the Order of International Joint Commission-1921 agreements. A fragmented approach at the sub-basin scale or within the administrative border has the potential to hinder basin-scale water resources management.

Historically, the SaskRB experienced many extreme hydrological events such as floods and droughts, which had a severe impact on the economy and environment. Also, the basin is highly vulnerable to climate change that increases the uncertainty of supply and demand across the basin. Due to the extensive anthropogenic activities, the SaskRB, in particular, the southern part of the basin, is already in a water-stressed condition. Meanwhile, different administrations are planning for new infrastructure, e.g., irrigation expansion, construction of reservoirs, hydropower plants, or diversion works, to meet the increasing water demand. These challenges due to natural and anthropogenic activities, and associated social, economic, and environmental impacts follow the basin boundary instead of the political border. Therefore, relying on fragmented water management cannot serve the need for basin-scale water resources planning and management effectively. A basin-scale water management model is a valuable tool that would help the decision-makers to answer many policy questions that follow the basin boundary.

In light of these needs, the present study developed a total of seven water allocation models for different regions of the SaskRB. These sub-models include (1) TAU model, for the TransAlta Utilities located in the upstream of the Bow River, (2) HRDP model, for the Highwood River regions, (3) STRIBS model, for the Sothern Tributaries of the Oldman River, (4) SSR-AB model, for the South Saskatchewan River in Alberta, (5) SSR-SK model, for the South Saskatchewan River in Saskatchewan, (6) NSR-AB model, for the North Saskatchewan River in Alberta, and (7) NSR-SK model, for the North Saskatchewan River in Saskatchewan. These seven sub-models were integrated into one to develop a basin-scale water management model for the SaskRB, called herein IWMSask. All the sub-models were developed based on the current water management infrastructure. The sub-model development process of the South Saskatchewan River Basin in Alberta (SSR-AB) and Saskatchewan (SSR-SK) was guided by the existing Water Resources Management Model (WRMM). The system properties, in general, were obtained from the historical measured data and scientific literature. Also, via what-if scenario analyses, this study assessed the sensitivity of reservoir storage, shortages in irrigation and non-irrigation water supply, environmental flow requirements, viability of transboundary apportionment agreements, and hydropower production to changing streamflow and irrigation demand conditions.

3.2 Research Findings

The development of IWMSask is a first step toward basin-scale water resources management in the SaskRB. The sub-models can be useful for the sub-basin scale water management planning to decision-makers and stakeholders. Meanwhile, the IWMSask will provide a platform for a better understanding of the functionalities of the complex water resources system in the SaskRB. The IWMSask will also help the decision-makers to analyze and answer policy questions that require a basin-scale water allocation model. For instance, increasing natural and human activities which involve climate change-induced demand and supply variability, extreme hydrological events, construction of new reservoirs or hydropower plants, expansion of irrigation projects, and changes of water management policy, are interconnected phenomena and have long term consequences on the society, environment, and economy of the basin. The IWMSask can be a useful tool for decision-makers and stakeholders to examine the impacts of such activities and changes across the basin.

The application of the IWMSask demonstrated the sensitivity of different water resources components of the SaskRB under changing streamflow and irrigation demand conditions. The results show that under current operational policy, a 10% decrease in streamflow coupled with a 10% increase in irrigation demand would (1) reduce reservoir storage, particularly in the Bow, Oldman, SSR-SK and SaskR sub-basins, (2) increase annual irrigation shortage in Bow, followed by Oldman, SSR-SK, and Red Deer sub-basins, and non-irrigation shortage in Bow, followed by Red Deer and Oldman sub-basins, (3) satisfy minimum streamflow requirements at environmentally important locations due to their higher priority in the operating policy, (4) increase the number of years when apportionment agreement is violated in the SSR, and (5) reduce average hydropower production in the Red Deer, Bow, NSR-AB, SSR-SK, and SaskR sub-basins. The depletion of reservoir storage would create difficulties for recreational activities and pumping for irrigation. Meanwhile, the reduction in hydropower production might create stressful conditions to meet the energy requirement of this region.

3.3 Limitations and Future Work

Water resources system properties were not readily available for some regions of the SaskRB, e.g., TAU, HRDP, STRIBS, NSR-AB, and NSR-SK, and the present study assumed those properties based on the historical observed data and information available in the literature. Investigating the actual operational properties for these regions could be an option for future research to improve model simulations further. A large number of water resource components from multiple jurisdictions with complex operating policies were modeled in the IWMSask that will create new opportunities for future work on incorporating other dimensions of water security such as economic, social, water quality, and others. The consideration of uncertainty in the demand and supply due to climate change or human interventions in future research would increase the robustness of the IWMSask in the decision-making process. Future work may also involve scenario-based policy analysis considering new infrastructure development, e.g., new reservoirs, hydropower plants, diversion work, or irrigation expansion. In addition, the consideration of climate change scenarios and associated impacts on hydrology and water resources in future research would be helpful to assess social, environmental, and economic vulnerabilities under climate change. A formal inclusion of uncertainty in climate, hydrology, policy, and society in the process of water management and decision support can be facilitated by new formal frameworks for sensitivity and uncertainty analysis such as Variogram Analysis of Response Surface (VARS) (Razavi and Gupta, 2016a, 2016b; Razavi *et al.*, 2019).

3.4 References

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Appendix A: Water Resources Decision Support System (DSS)

A.1 Water Resources Management Model (WRMM)

The Water Resources Management Model (WRMM) is a surface water allocation model developed by Alberta Environment (2002) for water resources planning and management in the South Saskatchewan River Basin (SSRB). WRMM is a Linear Programming based model that utilizes a penalty point system for water allocation to minimize an overall system penalty. For instance, if A is an arc of a network of ordered pairs (i, j) that contains a total of N nodes where the objective function is to minimize overall system penalty or cost, then the problem can be formulated as following (Islam and Gan, 2014):

$$\text{Min } Z = \sum_{(i,j)\in A} c_{ij}x_{ij} \ \ \forall\, i, j \in N \qquad (A.1)$$

Subject to:

$$\sum_{i} x_{ij} - \sum_{i} x_{ji} = 0 \ \ \forall\, j \in N \qquad (A.2)$$

$$0 \le l_{ij} \le x_{ij} \le u_{ij} \ \ \forall\, (i, j) \in N \qquad (A.3)$$

where, $c_{ij}, x_{ij,}$ u_{ij} and l_{ij} are the cost or penalty per unit flow, flow value, upper and lower bound of the flow along arc (i, j), respectively.

The Alberta Environment and Parks (AEP) uses WRMM in long term basin planning, utilizing historical data to represent future conditions as well as short term future consequences of different operational strategies. The model can represent an extensive network of rivers, reservoirs, and diversions, several water use options, return flow from irrigation fields, hydropower production, and a variety of water allocation priorities. All consumptive water demands are categorized into three groups, e.g., Major (non-irrigation), Minor (senior-most non-irrigation license holders), and Irrigation (private and district). The Major demand involves municipal and industrial water uses, which follows optimization objective function while the Minor demand contains important consumptive demands, e.g., rural, small municipal, and industrial uses, which is mandatory to meet under any circumstances. The Major and Minor demands are fixed throughout the simulation period, which is obtained based on the water policy of 2010 (Gonda, 2015), and the irrigation demand is estimated by the Irrigation Requirement Model (IRM) that was initially developed by the AEP and later upgraded by the Irrigation Branch of Alberta Agriculture, Food and Rural Development (AAFRD) (Irrigation Water Management Study Committee, 2002). The IRM evaluates water demand and return flow of irrigation districts based on different crop mixes, soil types, and irrigation methodology under the historical meteorological conditions. There is no return flow from Minor demand points; however, depending on the users, Major and Irrigation demand points can have return flow to the main system through small diversion channel. In that case, the withdrawal requirement of Major and Irrigation demand, which has return flow, is equal to the sum of consumptive demand and return flows. Apart from the consumptive demand, WRMM also has non-consumptive demands, e.g., hydropower production and minimum streamflow requirements for environmental and apportionment needs.

In WRMM, each component of the system has an ideal level or zone that represents the desired operational state of that component (Figure A.1 - A.3). There are also additional zones above and below the ideal zone to represent deviations. If sufficient water supply is available to meet all ideal demands, the ideal states are maintained; otherwise, water is allocated according to the specified set of operating policies. There is no penalty value for an ideal state, and each operating zone above and below the ideal state has a penalty value. A priority is assigned based on the penalty values of water users or zones, which is an arbitrary number selected after the calibration and validation process. During the model simulation, deviations first occur in those zones having low penalty values and then proceed into zones having higher values.

The water is allocated to each component based on the priority such that the overall system penalty is minimal. To explain further, consider a water allocation network with one reservoir, two demand nodes, one natural channel, and one diversion channel (Figure A.4). The reservoir has two storage zones, e.g., minimum and maximum storage zone, and a penalty value of 1000 if storage drops below the minimum or exceeds the maximum level. There is no minimum flow requirement and penalty value for the diversion channel (C1) that transports water to the municipal demand point, which has a constant demand of 10 m^3/week with a penalty value of 650. Another demand node for irrigation that has a constant 20 m^3/week demand with a penalty value of 600. A natural channel (C2) connects the reservoir and irrigation demand node, has a minimum flow requirement of 15 m^3/week, and a penalty value of 900. Consider that x1, x2, and x3 are allocated water to municipal, irrigation, and natural channel, respectively, then the WRMM system and objective function can be represented by Figure A.4.

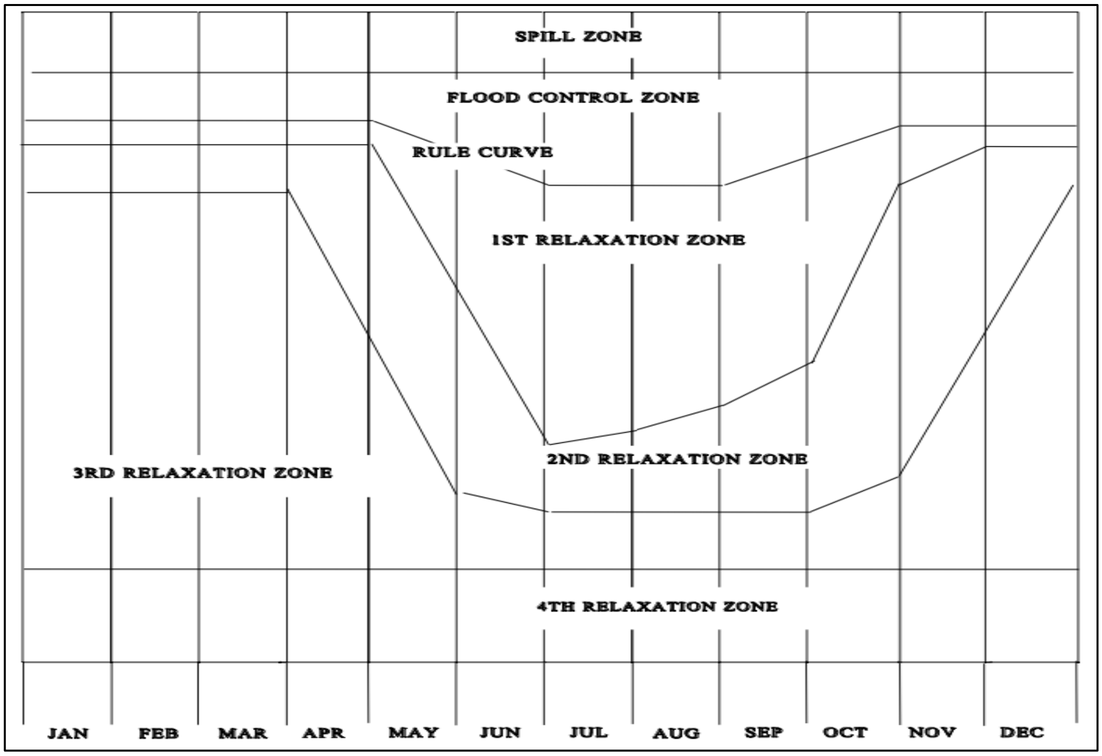


Figure A.1 Reservoir operating zones in WRMM (Alberta Environment, 2002)

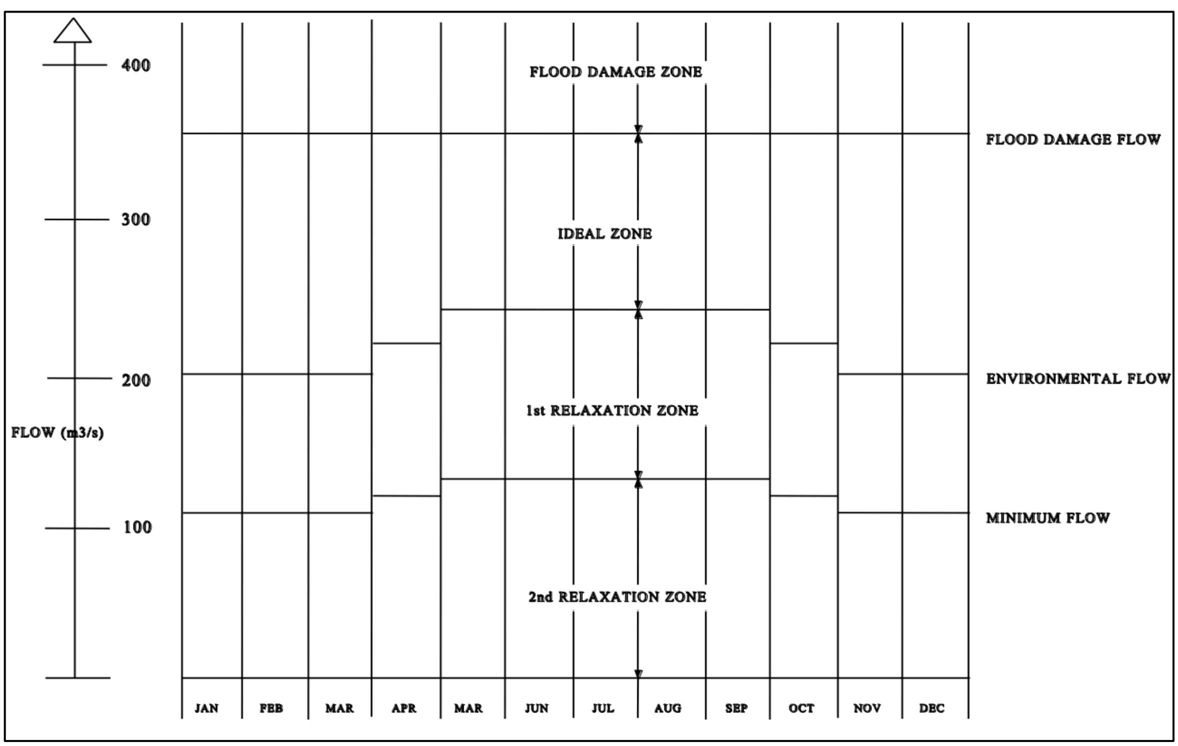


Figure A.2 Flow zones of natural channel in WRMM (Alberta Environment, 2002)

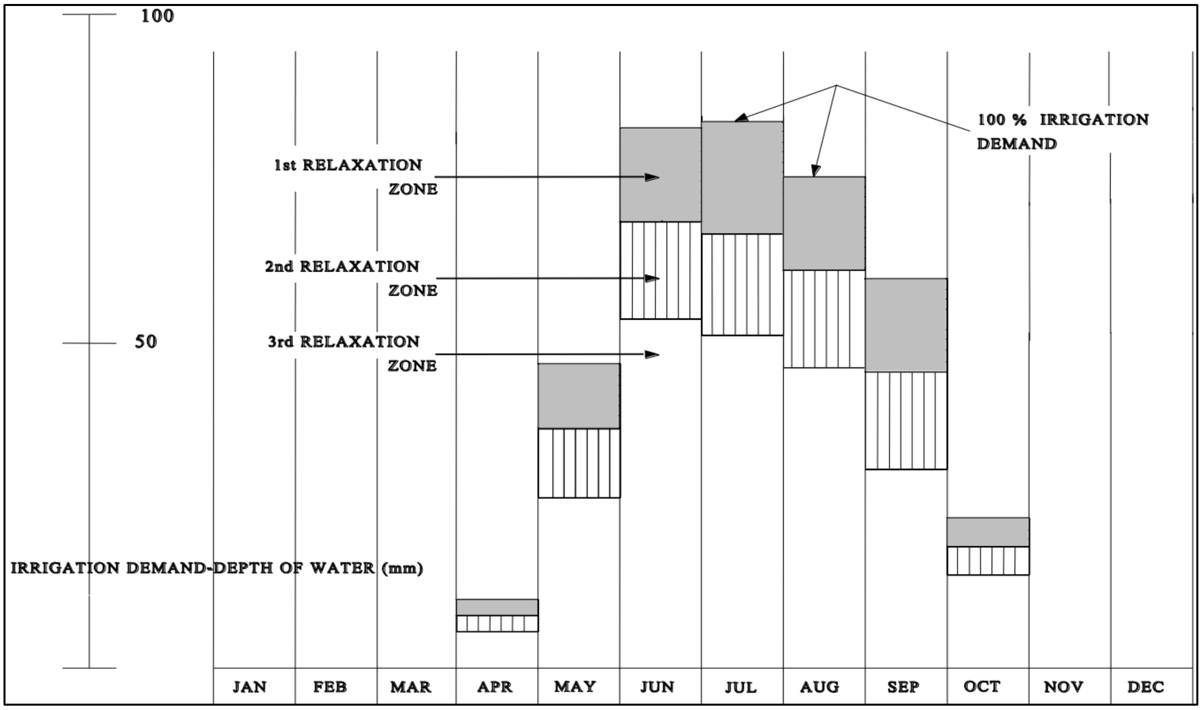
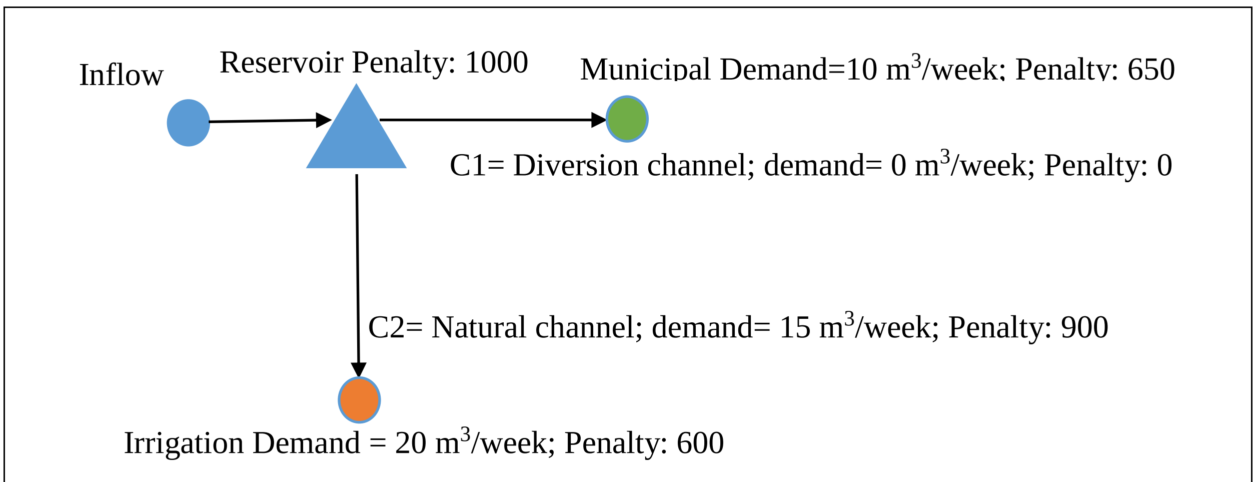


Figure A.3 Priority zones of irrigation demand node in WRMM (Alberta Environment, 2002)



$$\text{Objective} = \text{Min}[1000(\text{target elevation} - \text{simulated elevation}) + 650(10 - x1) + 600(20 - x2) + 900(15 - x3)$$

Figure A.4 A simple network that depicts WRMM problem formulation and objective function of water allocation

WRMM requires four basic sets of data to simulate a river system, which involves physical system properties, system priorities defined by the operating policy, water supply, and demand data. All this information is incorporated into the Simulation Control File (SCF), which is a primary data file used to execute WRMM. For long term basin planning, the model uses historical climatic inputs, e.g., precipitation, evaporation, inflows, and outflows, which are stored in a sub-file called Hydrometeorologic Base Data File (HBDF). A time-lag option is also available in WRMM and can simulate weekly, monthly, and yearly time steps. After the simulation, WRMM generates two files, e.g., OUTSIM and OUTID. The OUTSIM file contains simulation results of WRMM for all components of the system, while the OUTID file contains the ideal state of those components for each time step.

A.2 MODSIM Decision Support System (DSS)

MODSIM is a generalized river basin network model, developed at the Colorado State University (Shafer and Labadie, 1978) for long term river systems operational planning and short-term management. It is the longest, continuously maintained river basin management software package currently available (Labadie and Larson, 2007). MODSIM is widely used to represent complex river systems and resolving conflicts between urban, agricultural, and environmentally concerned stakeholders all over the world (Labadie, 1995).

In MODSIM, components of the system are represented as a network of nodes connected by links or arcs. A complete representation of the MODSIM network is shown in Figure A.5, where the solid lines represent user-defined channels, e.g., natural or diversion channels, whereas the dashed lines are generated automatically behind the user interface to ensure the mass balance of the entire system. MODSIM allocates water in a river basin through a sequential solution of a network flow optimization problem for each time step and allocates water based on water rights and other priority structures. For instance, if A is the set of all arcs or links in a river basin network and N is the set of all nodes, the problem can be formulated as follows (Labadie and Larson, 2007):

$$\text{Minimize} \sum_{k \in A} c_k q_k \qquad (A.4)$$

Subject to:

$$\sum_{k \in O_i} q_k - \sum_{j \in I_i} q_j = b_{it}(q) \text{ for all nodes } i \in N \qquad (A.5)$$

$$l_{kt}(q) \le q_k \le u_{kt}(q) \text{ for all links } k \in A \qquad (A.6)$$

$$c_k = -(50000 - 10 * p_k) \text{ for all links } k \in A \qquad (A.7)$$

where q_k is the flow rate in link k; O_i is the set of all links originating at node i; I_i is the set of all links terminating at node i, b_{it} is the gain or loss at node i at time t; l_{kt} and u_{kt} are specified lower and upper bounds of flow, respectively in link k at time t; c_k is the cost per unit flow rate in link k; and p_k is an integer priority ranking from 1 to 5,000 that determines how MODSIM allocates network flows, where a lower number indicates a higher ranking and creates a larger negative cost.

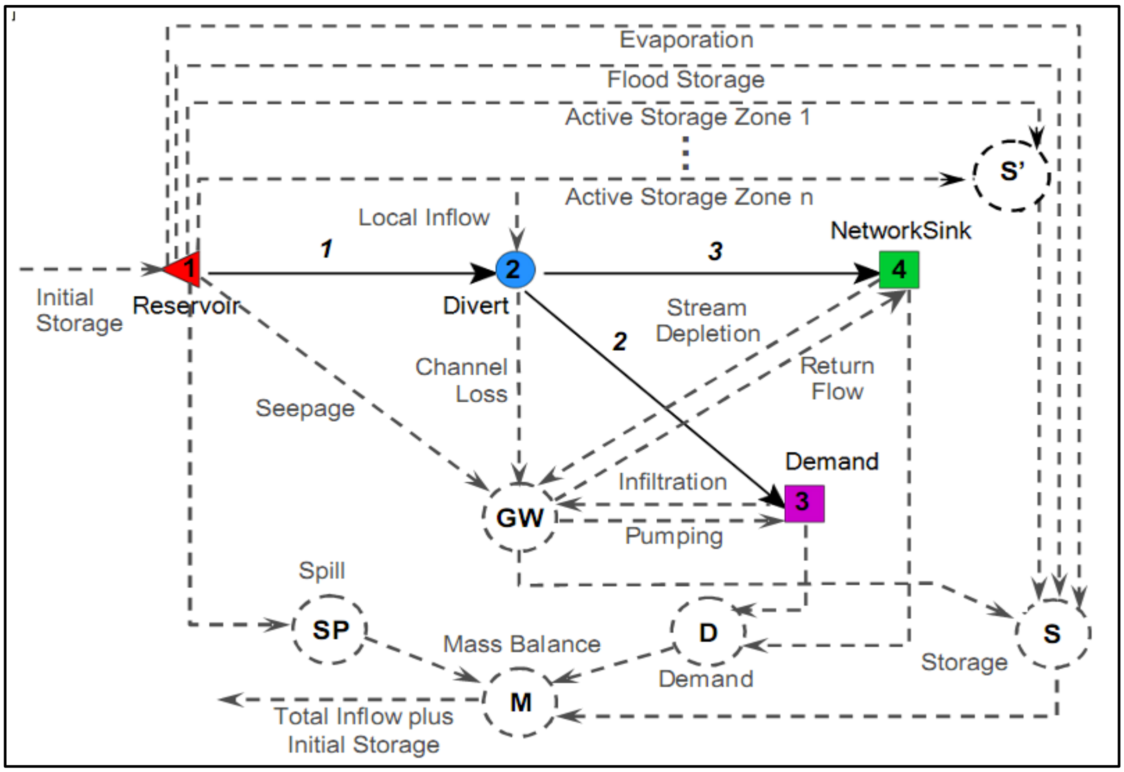


Figure A.5 MODSIM network structure with artificial nodes and links (Labadie and Larson, 2007)

MODSIM has many unique features and capabilities that distinguish it from other river basin management packages (Labadie and Larson, 2007). The Graphical User Interface (GUI) of MODSIM is very flexible to allow the representation of large complex river systems. For instance, all demand points and reservoirs are expressed as nodes, connected by links, and the user can easily assign respective properties, following which the GUI of MODSIM automatically generates the objective function and constraints of the network flow optimization model without requiring any computer programing by the user. Many complex water resources issues, e.g., environmental flow requirements, multiple operational zones, conditional operating policies in reservoirs, and short-term operation to long-term planning of the system, can easily be incorporated into the MODSIM platform. Also, MODSIM can model a wide variety of administrative mechanisms, e.g., water rights, storage contracts, rent pools, water banks, flow augmentation plans, and exchanges, with flexible system operations.

Moreover, the model includes hydrologic streamflow routing capabilities for daily simulation, e.g., Muskingum or user-defined time-lag options. MODSIM is developed under the Microsoft.NET framework, thereby allowing users to prepare the customized code in the Visual Basic.NET or C#.NET languages. This flexibility allows users to customize any features of the model or to integrate the water allocation model with other sub-models, e.g., hydrological, socio-economic, groundwater, or water quality sub-models, without re-programming and re-compiling the MODSIM source code. Besides, the scenario analysis option in the MODSIM package can reflect system performance under different scenarios in the same platform.

A.3 Overview and Comparison

Currently, many generic software platforms are available for representing river basin operations to address water security challenges at the basin level. An overview and comparison between WRMM and MODSIM DSS are presented in Table A.1 and Table A.2. In addition, overviews and comparisons of commonly used decision support systems (DSSs) are also presented in Table A.3 and Table A.4.

Table A.1 Overview and comparison of general properties of WRMM and MODSIM DSS

Program Name	**WRMM**	**MODSIM**
Developed By	Alberta Environment and Parks, initially in 1979	Colorado State University, initially in 1978
Software Full Access	N/A*, limited access with permission	YES, available for public access
Cost	Non-commercial	Non-commercial
GUI	YES	YES
GIS Interface	N/A	YES
Time Step	Multiples of 1-day	Multiples of second and 1-day
Allocation Algorithm	Out-of-Kilter Algorithm	Lagrangian Relaxation Algorithm
Watch Logic	N/A	YES (flow and storage conditions)
API and Languages Support	N/A	Developed in .NET Framework, provides a single API, and managed under Common Language Runtime (CLR)
Internal Scripting Interface	N/A	YES (VB.NET and C#)
Calibration Algorithm	N/A	Custom Network Calibration by loss and gain
Input Data Format	ASCII	ASCII, CSV
Output Data Format	ASCII	ASCII, CSV, MSDB
Demand Sites	All types of consumptive and non-consumptive demands	All types of consumptive and non-consumptive demands

* N/A= Not Available

Table A.2 Overview and comparison of important features of WRMM and MODSIM DSS

Program Name	**WRMM**	**MODSIM**
Reservoir Operation	YES	YES
Conditional Operating Rules	N/A*	YES (with pre-defined Hydrologic State)
Hydropower Modeling	YES	YES
Reservoir Operating Zones	YES, Time variant, 2 and 5 above and below rule curve, respectively	YES, Not-Time variant, 0 and unlimited above and below rule curve, respectively
Environmental Flow Requirements	YES (limited to 3 zones)	YES (any number of zones)
Operating Zones in Demand	YES (limited to 4 zones)	N/A
Return Flow	YES	YES
Water Rights and Storage Contracts	N/A	YES
Streamflow Routing	User-specified time lag	Muskingum and User-specified time lag
Monte Carlo Analysis	N/A	YES (inflow and demand)
Scenario Analysis	N/A	YES
Groundwater Modeling	N/A	YES, through customization
Water Quality Modeling	N/A	YES, through customization
Water Pricing and Economic Evaluation	N/A	YES, through customization
Rainfall-Runoff Modeling	N/A	YES, through customization
Irrigation Demand	YES	YES, through customization
Reference(s)	WRMM Manual	MODSIM Manual

* N/A= Not Available

Table A.3 (a) Overviews and comparisons of different decision support systems used for water resources management and planning

#	1	2	3	4	5	6	7	8
Program Name	WEAP	MIKE HYDRO Basin	Colorado DSS	RiverWare	HEC-ResSim	FreeWAT	SWAM	CaWAT
Cost	Commercial	Commercial	FREE	Commercial	FREE	FREE	N/A for public use	N/A
Allocation Algorithm	Prioritized (lp-solve)	Prioritized (Fraction of flow)	Prioritized, (MDSA)	Flexible Rule-based allocation (CPLEX)	Only Release Allocation	Water rights	Prioritized, (MDSA)	N/A
Timestep	1 – 365 days	Seconds	Daily and monthly	Hourly to yearly	N/A	N/A	Monthly	Monthly
Demand Types	Agriculture, Urban, Industry, and others	Agriculture, Urban, Industry, and others	Agriculture, Urban, Industry, and others	General Water Users	N/A	Irrigation	Agriculture, Urban, Industry, and others	N/A
GUI	YES	YES	YES	YES	YES	YES	YES	MS Excel Environment
API	YES	YES	N/A	N/A, but RCL	YES (only internal)	N/A	N/A	N/A
Scenario Analysis	YES	YES	YES	YES	YES	N/A	N/A	N/A
Rainfall-Runoff Modeling	Simplified FAO, MABIA, PGM, SMM	NAM, and UHM	N/A	N/A	N/A	N/A	N/A	Link to SWAT
Irrigation Demand	Based on FAO56	FAO 56	ASCE Pen-Mont	N/A	N/A	FAO 56	Blaney Criddle	Link to AquaCrop
Water Quality Modeling	DO, BOD, Temp. Link to Qual2k	BOD, DO, NH4, N/A3, P, user-defined	N/A	DO, TDS, TDG, Temperature	N/A	N/A	N/A	N/A
Groundwater Modeling	Link to MODFLOW and MODPATH	Linear reservoir (1-2 aquifers)	Link to MODFLOW	N/A	N/A	MODFLOW	N/A	N/A
Reservoir Operation	YES	YES	YES	YES	YES	N/A	YES	N/A
Financial Analysis	Simple Cost - Benefit	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Internal Scripting Interface	VBS, PHP, Ruby, Python, Perl, JS	N/A	Self-developed commands	RiverWare Policy Language	Jython	N/A	N/A	N/A
Hydropower Modeling	YES	YES	N/A	YES	YES	N/A	N/A	N/A

Table A.4 (b) Overviews and comparisons of different decision support systems used for water resources management and planning

#	1	2	3	4	5	6	7	8
Program Name	WEAP	MIKE HYDRO Basin	Colorado DSS	RiverWare	HEC-ResSim	FreeWAT	SWAM	CaWAT
Calibration Algorithm	PEST Algorithm	SCE and PSE	N/A	N/A	YES	UCODE_2014	N/A	N/A
Input Data Format	Manual Time series, Excel/delaminated text	.dfs0 and shapefiles	ASCII	N/A	HEC-DSS time series files	ASCII, istSOS, .sqlite	N/A	MS Excel Environment
Output Data Format	Graphical Maps, Time series (ASCII, Excel)	.dfs0 and shapefiles	ASCII, graphics	ASCII, Excel, HTML, graphics	ASCII, graphics	Graphics, ASCII	N/A	Tables, GIS maps
GIS interface	YES	YES	YES	YES	YES	YES	N/A	N/A
Linked to other models before?	SWAT	N/A	N/A	MODFLOW	HEC-HMS WEHY-HCM	N/A	N/A	SWAT, and AquaCrop
Automation	YES	YES	N/A	YES	YES	N/A	N/A	N/A
Languages Support by API	VB/S, C, Python, MATLAB, and others (COM)	Any .NET compatible prog. language	N/A	N/A	Jython (only internal)	N/A	N/A	N/A
Website	http://www.weap21.org	https://www.mikepoweredbydhi.com	http://cdss.state.co.us	http://www.riverware.org	http://www.hec.usace.army.mil/	http://www.freewat.eu	https://cdmsmith.com	CaWAT website
References	WEAP Online Help	Hydro Basin Manual, Auto calibration Manual, and Interface Programming Guide	StateMod Manual, StateCU Manual, and StateDGI Manual	RiverWare User Guide	HEC-ResSim Quick Start, and HEC-ResSim Manual	FreeWAT Manuals	SWAM Manual	CaWAT Article and Project Brief

Note: Table A.3 and Table A.4 were prepared by the M.Sc. candidate and Kasra Keshavarz (M.Sc. student, Global Institute for Water Security, University of Saskatchewan)

A.4 References

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Appendix B: Supplementary Materials for the Water Management Model Development

Description:

This section of the appendix provides details information about the system properties, which were considered to develop water allocation models for different regions of the SaskRB.

A total seven water allocation sub-models were developed for the SaskRB which includes (1) South Saskatchewan River in Alberta (SSR-AB), (2) South Saskatchewan River in Saskatchewan (SSR-SK), (3) TransAlta Utilities (TAU), (4) Highwood River Diversion Plan (HRDP), (5) Southern Tributaries (STRIBS), (6) North Saskatchewan River in Alberta (NSR-AB), and (7) North Saskatchewan River in Saskatchewan (NSR-SK).

The model development process of the SSR-AB and SSR-SK was guided by the existing WRMM models of Alberta and Saskatchewan. Details system properties, e.g., reservoir physical and operational characteristics, hydropower plants information, natural and diversion channel capacity, environmental flow needs, transboundary apportionment agreement needs, irrigation, and non-irrigation demand and associated return flow to the system, and others, were collected from the WRMM models and translated to MODSIM DSS environment.

The existing water management models for other regions were not readily available; therefore, this study developed those models based on the water management reports and associated scientific publications. A details description of those sub-model development process was provided below for further research works.

(3) TransAlta Utilities (TAU): Appendix C

(4) Highwood River Diversion Plan (HRDP): Appendix D

(5) Southern Tributaries (STRIBS): Appendix E

(6) North Saskatchewan River in Alberta (NSR-AB): Appendix F

(7) North Saskatchewan River in Saskatchewan (NSR-SK): Appendix G

Appendix C: TransAlta Utilities (TAU)

C.1 Introduction

The Bow River is a tributary of the South Saskatchewan River (SSR) and one of the principal watercourses in the Saskatchewan River Basin (SaskRB), delivering water from the Rocky Mountains to the downstream prairies, and plays a crucial role economically and environmentally. In 1911, TransAlta Corporation (TAC), a privately owned company, started hydropower generation in the upstream part of the Bow River (Figure C.1), and since then, the flow has been controlled by dams and reservoirs. The TAC is mainly responsible for the storage and release of water to downstream rivers and tributaries (WaterSMART, 2016), which has a significant influence on downstream socio-economic development and environmental stability. Loss of glacier storage in the upstream, rapid growth of population and water demand, and observed periodic low flows in the downstream, making the Bow River basin water resources more challenging for future development (WaterSMART, 2016). Also, the TAC is conducting maintenance and rebuilding critical infrastructures over the next several years, which might have an impact on the downstream water management policy (WaterSMART, 2016). Therefore, for long term planning and decision making, integration of the TAU into the main water management framework is vital to explore opportunities for better management of the river system.

The primary objective of the TAU is to provide hydroelectric facilities that involve equalize power production throughout the year, store water during high flow periods and release during low flow periods, and finally, modify river flows on a seasonal basis for drought and flood management in downstream. There are eleven hydropower plants in the TAU, six of which are storage reservoir based, and the rest of them are run-off-the-river (RR) hydropower plants and altogether producing 335 MW of electricity. Currently, there is no consumptive demand or other facilities in the system.

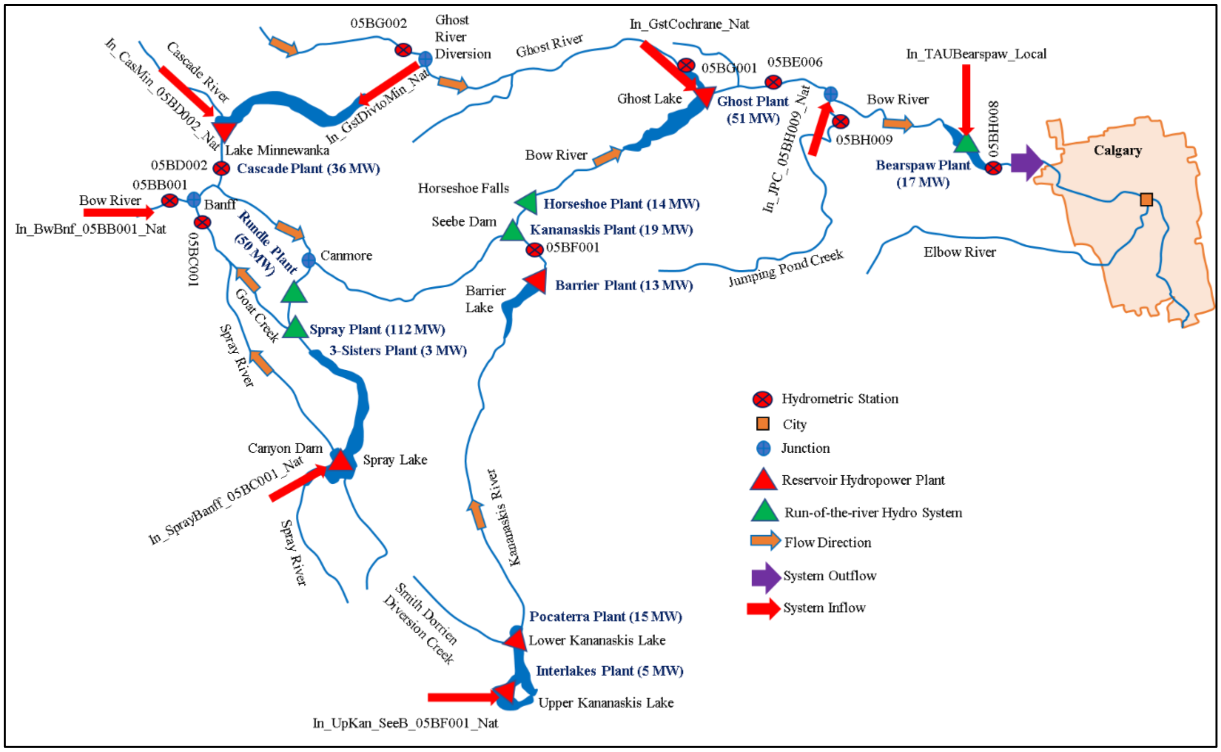

Figure C.1 Water resources system diagram of the TransAlta Utilities (TAU) located in the upstream of the Bow River, Alberta

C.2 Reservoir Properties

C.2.1 General Properties

The TAU water resources system has six storage reservoirs. To determine reservoir's active storage capacity, historical recorded weekly mean elevation of all reservoirs were collected from the South Saskatchewan River Basin Weekly Natural Flow Database (SSRB Database) (Alberta Environment, 1998) and then based on the historical maximum value of recorded data, reservoir's Full Supply Level (FSL) was determined. The minimum capacity of respective reservoirs was considered based on the elevation below which the reservoir reaches its dead storage level (DSL) (Table C.1). The difference of storage at DSL and FSL will then represent the storage capacity of the TAU reservoirs.

Table C.1 Historical minimum and maximum elevation of the TAU reservoirs collected from the SSRB Database

Sl.	Reservoir Name	First on Stream	Minimum Elevation (m)	Maximum Operating Level (MOL) (m)	Storage Capacity (MCM)	Latitude	Longitude
1.	Spray	1950	1685.23	1701.86	256	50.911667	-115.339444
2.	Upper Kananaskis	1932	1685.37	1701.80	126	50.618056	-115.154167
3.	Lower Kananaskis	1955	1653.56	1667.01	63	50.656111	-115.136944
4.	Barrier	1948	1365.44	1376.14	25	51.027222	-115.065556
5.	Minnewanka	1917	1464.58	1475.27	223	51.258056	-115.373056
6.	Ghost	1932	1184.19	1191.96	72	51.2025	-114.756667

*Meter (m), Million Cubic Meter (MCM)

C.2.2 Reservoir Area-Capacity-Elevation (ACE)

For all reservoirs of the TAU system, Area, Capacity, and Elevation data were collected from the SSRB Database. The data obtained from this source included the reservoir's dead storage, which was subtracted from the ACE table based on the reservoir's active storage information provided in Alberta River Basins online portal (Alberta Environment, 2018a) and summarized in Table C.2.

Table C.2 Area (in square kilometer), Capacity (in cubic decameter) and Elevation (in meter) of the TAU reservoirs collected from the SSRB Database

Lake Minnewanka (Station ID:05BD003)					
Area	Capacity	Elevation	Area	Capacity	Elevation
19.55	0.00	1464.58	21.09	123539.35	1470.66
19.66	8225.63	1465.00	21.45	155950.25	1472.18
19.80	18061.58	1465.50	21.80	188097.14	1473.67
19.95	29667.80	1466.09	21.81	188915.90	1473.71
20.36	60382.50	1467.61	22.14	222405.80	1475.23
20.72	91683.17	1469.14	22.51	256519.16	1476.76

Ghost Lake (Station ID: 05BE005)					
Area	Capacity	Elevation	Area	Capacity	Elevation
7.44	0.00	1184.19	11.00	61557.65	1191.01
7.74	6274.04	1185.00	11.57	69898.48	1191.77
7.99	11450.79	1185.67	11.70	73087.02	1192.04
8.67	24141.14	1187.20	12.70	99482.41	1194.21
9.47	37963.06	1188.72	12.98	107312.06	1194.82
10.43	53129.14	1190.24			

Upper Kanaskis Lake (Station ID: 05BF005)					
Area	Capacity	Elevation	Area	Capacity	Elevation
6.41	0.00	1685.37	7.82	66184.54	1694.69
6.44	1076.21	1685.54	8.01	78245.47	1696.21
6.63	11030.98	1687.07	8.21	90608.16	1697.74
6.84	21290.54	1688.59	8.39	104019.36	1699.26
7.13	31932.64	1690.12	8.42	106199.33	1699.50
7.40	43006.78	1691.64	8.58	117711.74	1700.78
7.60	54438.31	1693.16	8.68	138748.02	1703.22

Lower Kanaskis lake (Station ID: 05BF009)					
Area	Capacity	Elevation	Area	Capacity	Elevation
2.73	0.00	1653.56	5.27	34285.13	1662.03
3.20	4470.64	1655.06	5.44	37715.18	1662.68
3.68	9710.15	1656.59	5.79	46266.34	1664.21
4.15	15671.28	1658.11	6.16	55369.95	1665.73
4.61	22347.92	1659.64	6.46	63063.67	1666.95
5.06	29718.75	1661.16	6.54	65046.48	1667.26

Barrier Lake (Station ID: 05BF024)					
Area	Capacity	Elevation	Area	Capacity	Elevation
1.71	0.00	1365.44	2.38	12508.00	1371.60
1.72	101.12	1365.50	2.62	16319.52	1373.12
1.88	2839.74	1367.03	2.81	20342.14	1374.61
2.04	5822.21	1368.55	2.82	20464.04	1374.65
2.18	9032.52	1370.08	3.06	24942.32	1376.17

Spray Lake (Station ID: 05BC006)					
Area	Capacity	Elevation	Area	Capacity	Elevation
11.12	0.00	1685.23	16.05	125727.12	1694.69
11.25	3469.56	1685.54	17.03	150931.03	1696.21
11.87	21087.76	1687.07	17.13	153942.01	1696.38
12.52	39673.70	1688.59	17.92	177559.89	1697.74
13.23	59299.01	1690.12	18.76	205505.47	1699.26
14.04	80084.08	1691.64	19.59	234728.17	1700.78
14.91	102142.46	1693.16	20.26	265094.64	1702.31

C.2.3 Reservoir Operating Policy

The TAC is a privately owned company, and the operating policy of the TAU reservoirs was not available for public access or research purpose. The Government of Alberta (GoA) has been receiving water from the TAU to the Bow River downstream based on an agreement with the TAC. The recent agreement which is in place now has started in 2016 and will expire in 2021 (Government of Alberta, 2018). The objectives of this agreement were flood and drought mitigation in the downstream, in particular the city of Calgary. According to this agreement, the GoA can operate existing reservoirs at specific periods of the year, and in turn, the GoA will pay CAD 5.5 million per year to the TAC as compensation. Details of the agreement were adopted from the online portal of the Alberta Environment and Parks (Government of Alberta, 2018) and presented below:

"**Flood Management:** The agreement allows the Province to set elevations on the Ghost Reservoir during the period of May 16 to July 7 until 2021, which is typically the highest storm risk period of the year. By keeping the reservoir lower during this period, there is more space to store flood events, thereby, lowering peak flows downstream of the dam or, at the very least, delaying those peaks."

"**Drought Management:** The agreement includes the ability of the government to have TransAlta store water in the Kananaskis system to be used in periods of low flows in the Bow River. This part of the agreement is year-round for the duration of the agreement."

However, for model development and to represent historical operation (1928-2018), firstly, this study collected historical weekly mean elevation of six reservoirs above (Table C.1) for a different range of periods. Secondly, ten years (1992-2001) average of weekly mean elevation of respective reservoirs was considered as the target operating policy of those reservoirs (Figure C.2).

This study assumed that the last ten years of reservoir elevation represents the 20th century's TAU operating policy, which was applied to develop the TAU planning model for 91 years (1928-2018).

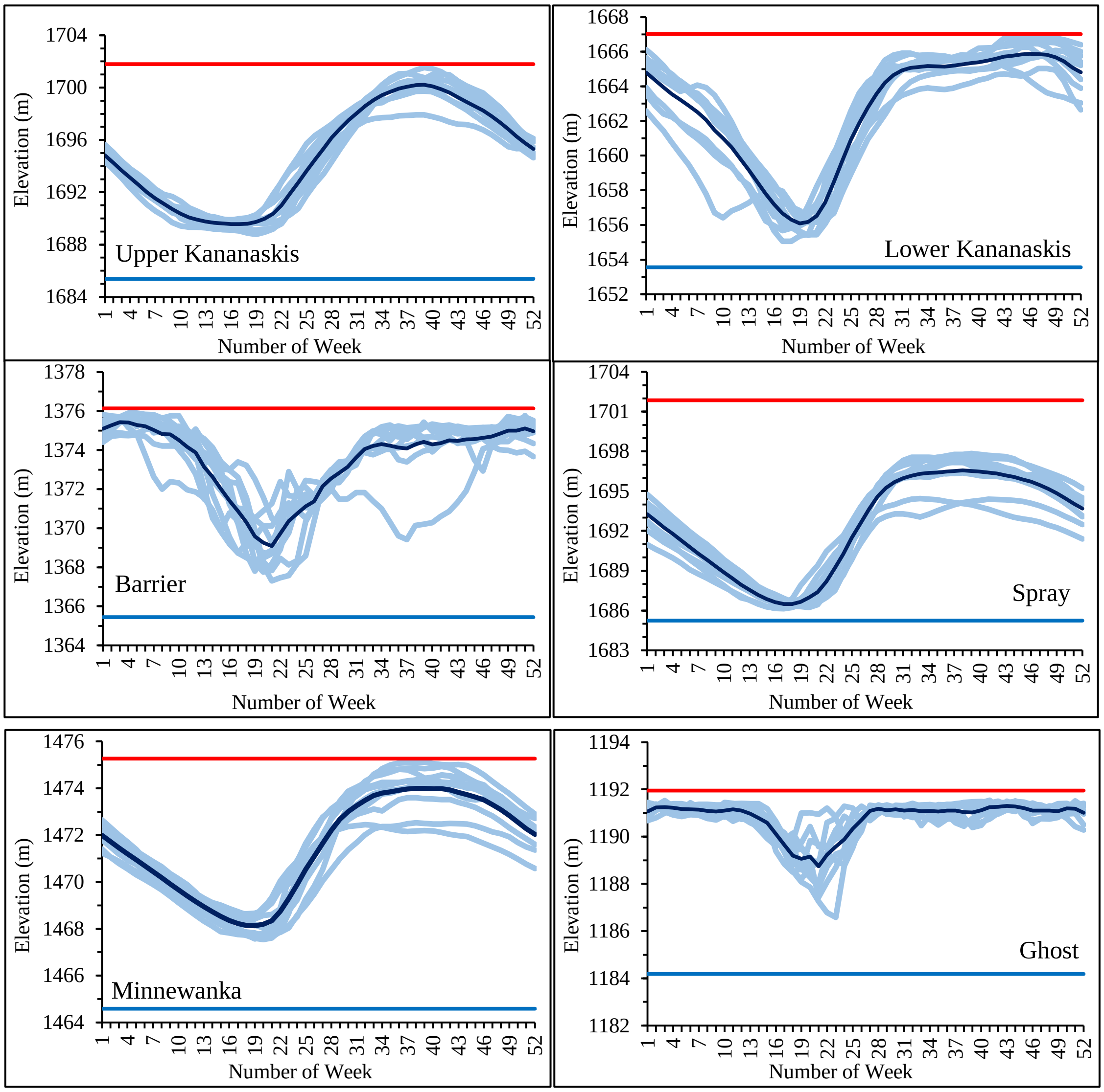

Figure C.2 Target elevation considered for different TAU reservoirs. The red, blue, and dark blue lines are representing maximum, minimum, and target elevation, respectively, and light blue lines in the background are representing recorded mean weekly elevation of reservoirs for ten years (1992-2001)

C.2.4 Reservoir Evaporation and Precipitation

The TAU is a small water resources system compared to the other part of the SSRB, and the outlet of this system ends near Calgary (Figure C.1). Therefore, this study used evaporation and precipitation data of Calgary to estimate net reservoir evaporation for the TAU reservoirs. The evaporation and precipitation data of Calgary station were collected from the online portal of Alberta Agriculture and Forestry (Government of Alberta, 2019b) and the WRMM Alberta model (Alberta Environment, 2002). The map of isohyetals of mean annual precipitation and evaporation for the SSRB was used to adjust the data of Calgary for the TAU reservoirs by the ratio of annual precipitation and evaporation in the TAU reservoir sites to those of Calgary (Table C.3). A similar strategy was also adopted in the WRMM Alberta model development to avoid missing data constraints. The net evaporation at each reservoir site was estimated by subtracting the weekly precipitation from corresponding weekly lake evaporation (Figure C.3). Negative net evaporation for a week indicates that the precipitation amount exceeded the evaporation amount for that week.

Table C.3 Evaporation and Precipitation station along with the weighting factor considered for the TAU reservoirs

Reservoir	Evaporation Station	Weighting Factor	Precipitation Station	Weighting Factor
Spray Lake	Calgary	0.88	Calgary	1.63
Lake Minnewanka	Calgary	0.89	Calgary	1.34
Ghost Lake	Calgary	0.94	Calgary	1.26
Upper Kananaskis	Calgary	0.87	Calgary	1.63
Lower Kananaskis	Calgary	0.87	Calgary	1.63
Barrier Lake	Calgary	0.90	Calgary	1.49

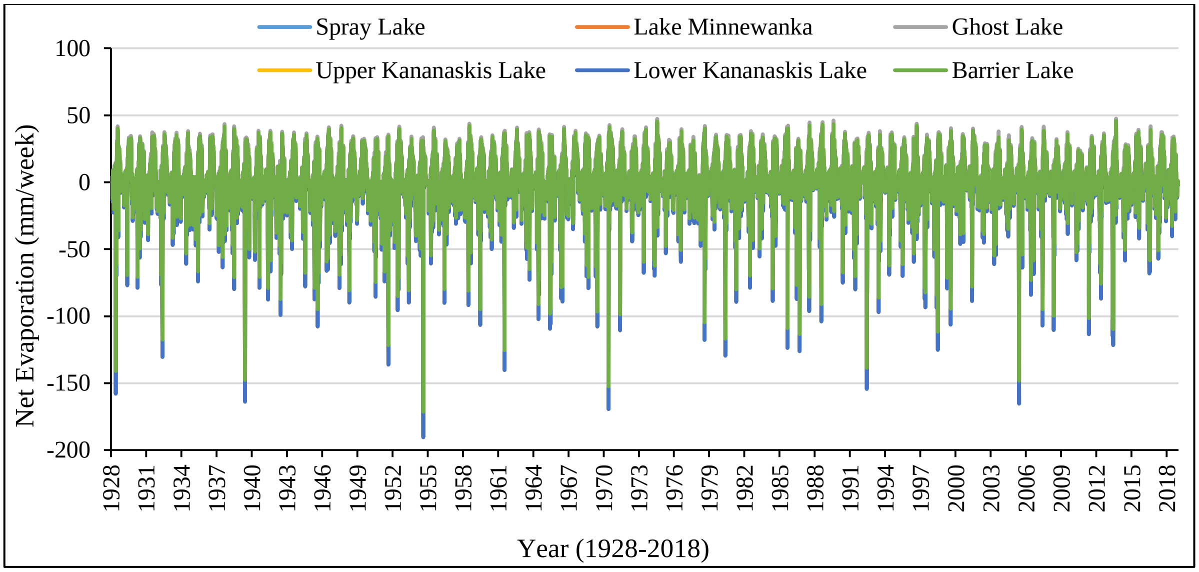

Figure C.3 Net reservoir evaporation considered in the TAU model development

C.3 Inflow Properties

The Bow River is the primary watercourse in the TAU system, which has four important tributaries, e.g., the Spray River, Cascade River, Kananaskis River, and Ghost River (Figure C.1). Also, some minor inflows are coming into the TAU system, which involves the Ghost River diversion to the Lake Minnewanka for power production in the Cascade hydropower plant, the Mud Lake diversion to the Lower Kananaskis Lake via Smith-Dorrien Creek, and Jumping Pond Creek to the Bow River after Ghost Dam.

For all watercourses, natural weekly mean flows were collected from the SSRB Database from 1912-2001 and then extended until 2018 based on the available gauge data. Also, there are some important inflows for which streamflow data were not available. For instance, the Ghost River diversion to Lake Minnewanka, which has a limited range of recorded data and was not sufficient for the model development. Therefore, based on the Ghost River state of the watershed report (GWAS, 2018), this study considered 63% of the Ghost River Natural flow at upstream of diversion works as Ghost River diversion to Lake Minnewanka. Additional inflows were also added to count local runoff contribution and ensure a mass balance of the system and termed as 'Incremental Flow (IF)'. A brief description of different inflows considered in the TAU model development process is presented in Table C.4.

Table C.4 Inflows of the TAU water resource system

Sl.	MODSIM Inflow Name	Inflow Type	Inflow ID	MAI* (MCM)
1	In_BwBnf_05BB001_Nat	Main	05BB001	1340
2	In_CasMin_05BD002_Nat	Main	05BD002	247
3	In_SprayBanff_05BC001_Nat	Main	05BC001	478
4	In_UpKan_SeeB_05BF001_Nat	Main	05BF001	467
5	In_GstDivtoMin_Nat	Main	63% of (05BG002)	44
6	In_GstCochrane_Nat	Main	05BG001-In_GstDivtoMin_Nat	182
7	In_JPC_05BH009_Nat	Main	05BH009	60
8	In_TAUBearspaw_Local	IF	05BH008-05BE006-05BH009	93

*MAI= Mean Annual Inflow; MCM= Million Cubic Meter

C.4 Channel Properties

Channel properties include the capacity of a channel to ensure minimum streamflow requirements (MSR) and avoid flood inundation along the riverbank. For the Bow River, this study adopted maximum and minimum river capacity from the WRMM Alberta model. For other streams and channels, historical natural weekly maximum and minimum flow values (1912-2018) were considered as the capacity of channels. However, minimum flow requirements vary over time and space, therefore for important channels, historical weekly minimum flows were considered for a different portion of a stream over 52 weeks of the year. The channel properties considered in this study are summarized in Table C.5, and minimum streamflow that varies over time and space is also presented in Figure C.4 below.

Table C.5 Channel properties of the TAU system considered based on the historical minimum and maximum streamflow values

Natural Channel	MSR (m^3/s)	Maximum (m^3/s)	Note
Kananaskis River: up to Barrier Lake	FT_KanBeforeBL	169	05BF001
Kananaskis River: after Barrier Lake	0	169	05BF001
Cascade River: Minnewanka to Banff	0	59	05BD002
Cascade Power Diversion to Banff	0	39.76	05BD004
Spray River: near Banff	FT_SBanff	107.59	05BC001
Spray River Power Diversion to Canmore	0	34.51	05BE007
Goat Creek	0	8.81	05BC008
Spray River near Canyon Dam	0	98.78	05BC001-05BC008
Bow River: Banff to Canmore	0	5000	WRMM*
Bow River: Canmore to Seebe Dam	0	5000	WRMM*
Bow River: Seebe Dam to Ghost Dam	0	5000	WRMM*
Bow River: Ghost Dam to Bearspaw Dam	0	5000	WRMM*
Bow River: Bearspaw Dam to Calgary	FT_BowBelBearspaw	5000	05BH008

*Note: Assumed based on the WRMM Alberta Model (Bow River)

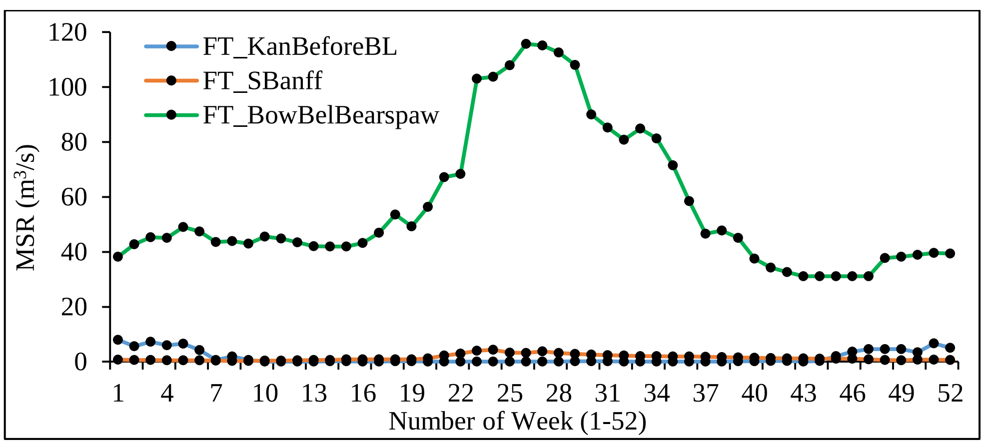

Figure C.4 Minimum streamflow requirements (MSR) for different rivers of the TAU system over 52 weeks of a year

C.5 Hydropower Plants

There are eleven hydropower plants in the TAU system, and together they can produce a maximum of 335 MW of electricity. Among eleven hydropower plants, six are storage based, and five are Run-of-the-river (RR) hydroelectric systems, and the TAC operates all of them. The tailwater head of all power plants was estimated based on the Gross head data that was collected from Alberta Energy's online resources (Alberta Utilities Commission, 2010). The head loss, turbine, and generator efficiency data were not available, and this study assumed a reasonable value for model development based on similar values used for different hydropower plants in the WRMM Alberta model. A brief description of all hydropower plants is presented in Table C.6 below.

Table C.6 Hydropower plant properties of the TAU system

Plant Name	First on Stream	Capacity (MW)	Storage Reservoir	Gross Head (m)	Head Loss (m)	Turbine Efficiency	Generator Efficiency
3 Sisters	1951	3	Spray	20	0.9	0.95	0.95
Spray	1951	112	RR	274	0.9	0.95	0.95
Rundle	1951	50	RR	98	0.9	0.95	0.95
Cascade	1942	36	Minnewanka	105	0.9	0.95	0.95
Interlakes	1955	5	Upper Kananaskis	38	0.9	0.95	0.95
Pocaterra	1955	15	Lower Kananaskis	66	0.9	0.95	0.95
Barrier	1947	13	Barrier	46	0.9	0.95	0.95
Kananaskis	1913	19	RR	22	0.9	0.95	0.95
Horseshoe	1911	14	RR	22	0.9	0.95	0.95
Ghost	1929	51	Ghost	34	0.9	0.95	0.95
Bearspaw	1954	17	RR	15	0.9	0.95	0.95

C.6 System Priority

The MODSIM Decision Support System allocates water based on the priority of water resource components assigned by the user. This study used a manual calibration approach to get priority rankings of this system where the objective was to keep reservoir elevation on target level and get desired streamflow, e.g., Bow River flow below Ghost Dam and before Calgary. The priority rankings that were used to develop the TAU planning model are tabulated below in Table C.7.

Table C.7 Priority of water resource system components considered in the TAU model development

Name of the Component	Node Type	MODSIM Priority
FT_KanBeforeBL	MSR	1
FT_SBanff	MSR	1
FT_BowBelBearspaw	MSR	1
Spray Lake	Reservoir	1
Ghost Lake	Reservoir	1
Upper Kananaskis Lake	Reservoir	2
Lower Kananaskis Lake	Reservoir	3
Barrier lake	Reservoir	4
Lake Minnewanka	Reservoir	5
Bearspaw Dam	RR	6
Rundle Pond	RR	6
Whitemans Pond	RR	6
Horseshoe Falls	RR	6
Seebe Dam	RR	6

C.7 TAU Schematic in MODSIM Graphical User Interface (GUI)

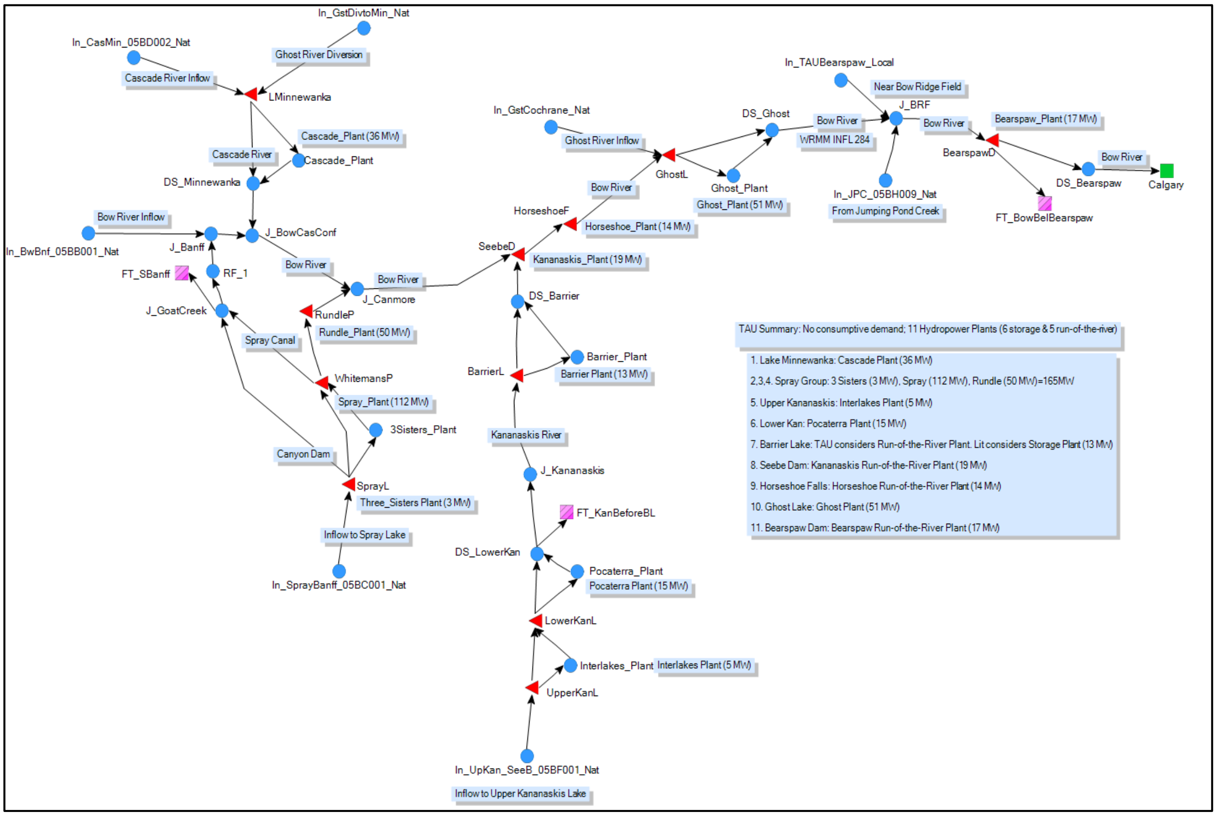

Figure C.5 Developed TAU model schematic in MODSIM GUI

C.8 Model Validation and Results

To validate the developed TAU model, this study compared MODSIM simulated results with that of WRMM and available observed data, between 1992 and 2001. The validation strategy adopted in this study is summarized in Table C.8.

Table C.8 A summary of strategies adopted to assess the credibility of developed TAU model

Category	Validation Strategy
Water Balance	**Total available water - Total outflow** = 0 **Error (%)** = (Total available water-Total outflow)/ Total available water **Total available water (TAW)** = Reservoir storage gain + Total inflow to the system + Total reservoir precipitation+ Total return flow to the system **Total outflow (TOF)** = Reservoir storage loss + Total outflow from the system + Total reservoir evaporation + Total allocation to consumptive demand
Streamflow	Comparison of MODSIM simulated streamflow with recorded gauge data and WRMM simulation results where available
Reservoir Elevation	Comparison of MODSIM simulated reservoir elevation with recorded gauge data

C.8.1 Water Balance of the TAU Model

Table C.9 Mean annual water balance of the developed TAU model

Category	TAU
Inflow from rivers (MCM)	54.651
Outflow to downstream (MCM)	54.574
Allocation to demand (MCM)	0.000
Reservoir storage gain (+) / loss (-) (MCM)	0.001
Reservoir evaporation (MCM)	0.447
Reservoir precipitation (MCM)	0.369
Return flow (MCM)	0.000
Total available water (MCM)	55.022
Total outflow (MCM)	55.021
Difference (MCM)	0.001
Error (%)	0.0011%

Note: MCM= Million Cubic Meter

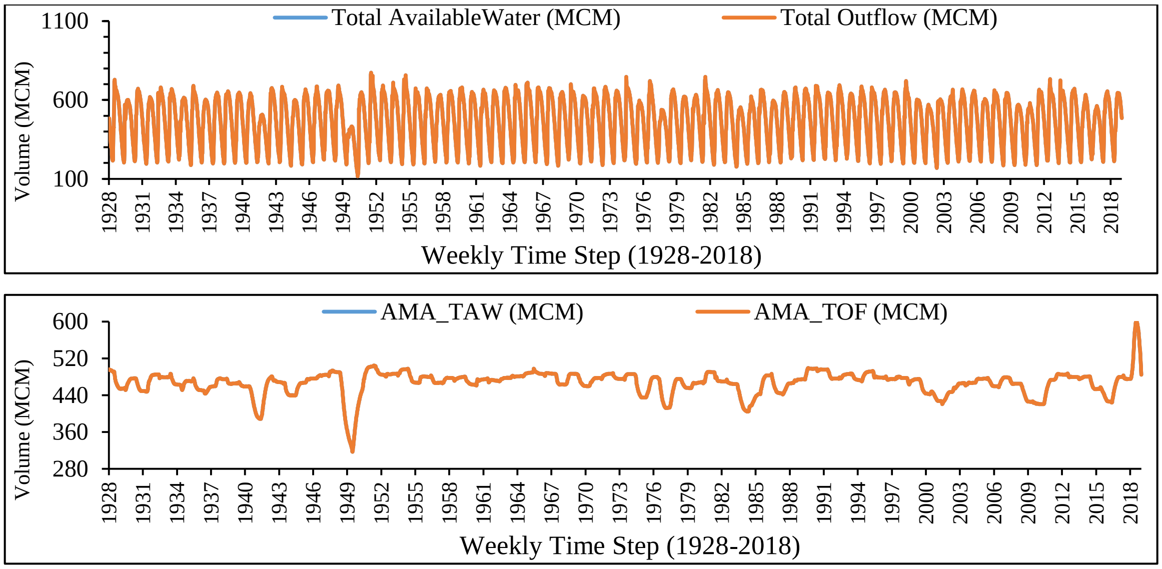

Figure C.6 Water balance of the TAU system after MODSIM simulation. The top plot is representing weekly water balance for each time step and the bottom plot representing their Annual Moving Average (AMA) of total available water (TAW) and total outflow (TOF).

C.8.2 MODSIM TAU Outflows

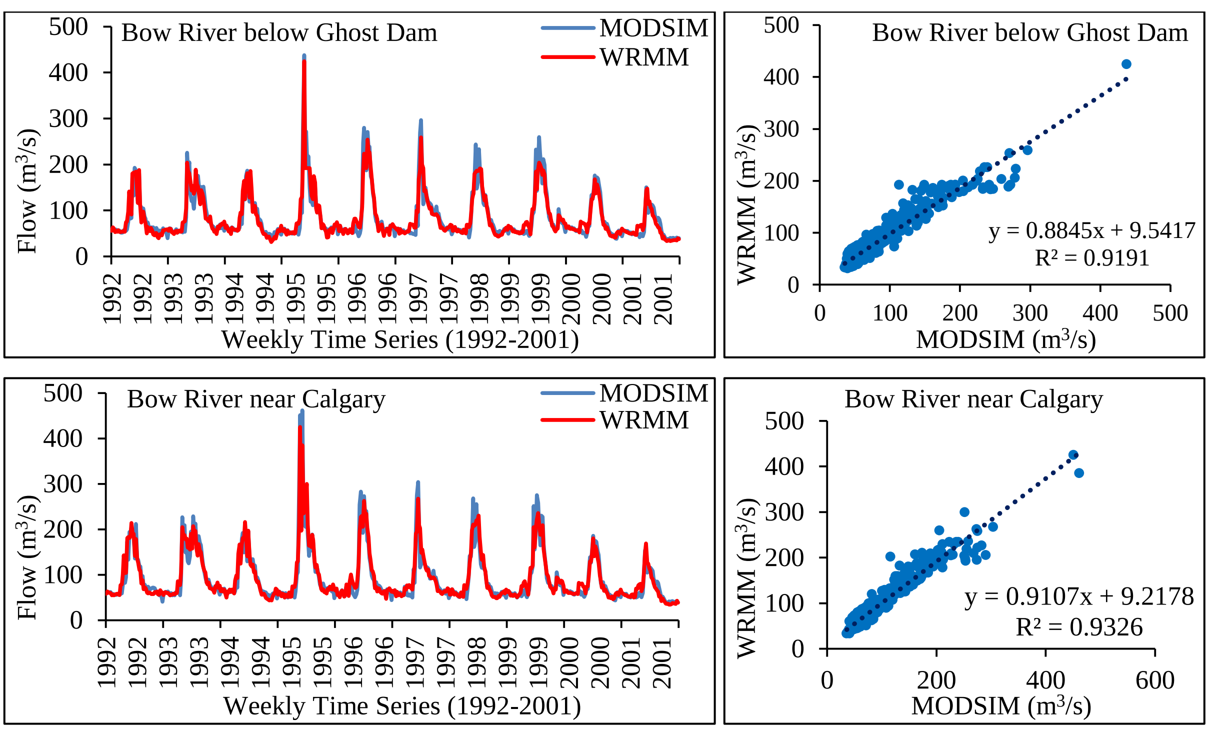

Figure C.7 MODSIM and WRMM simulation results for the Bow River below Ghost Dam (top) and near Calgary (bottom)

C.8.3 Reservoir Elevation

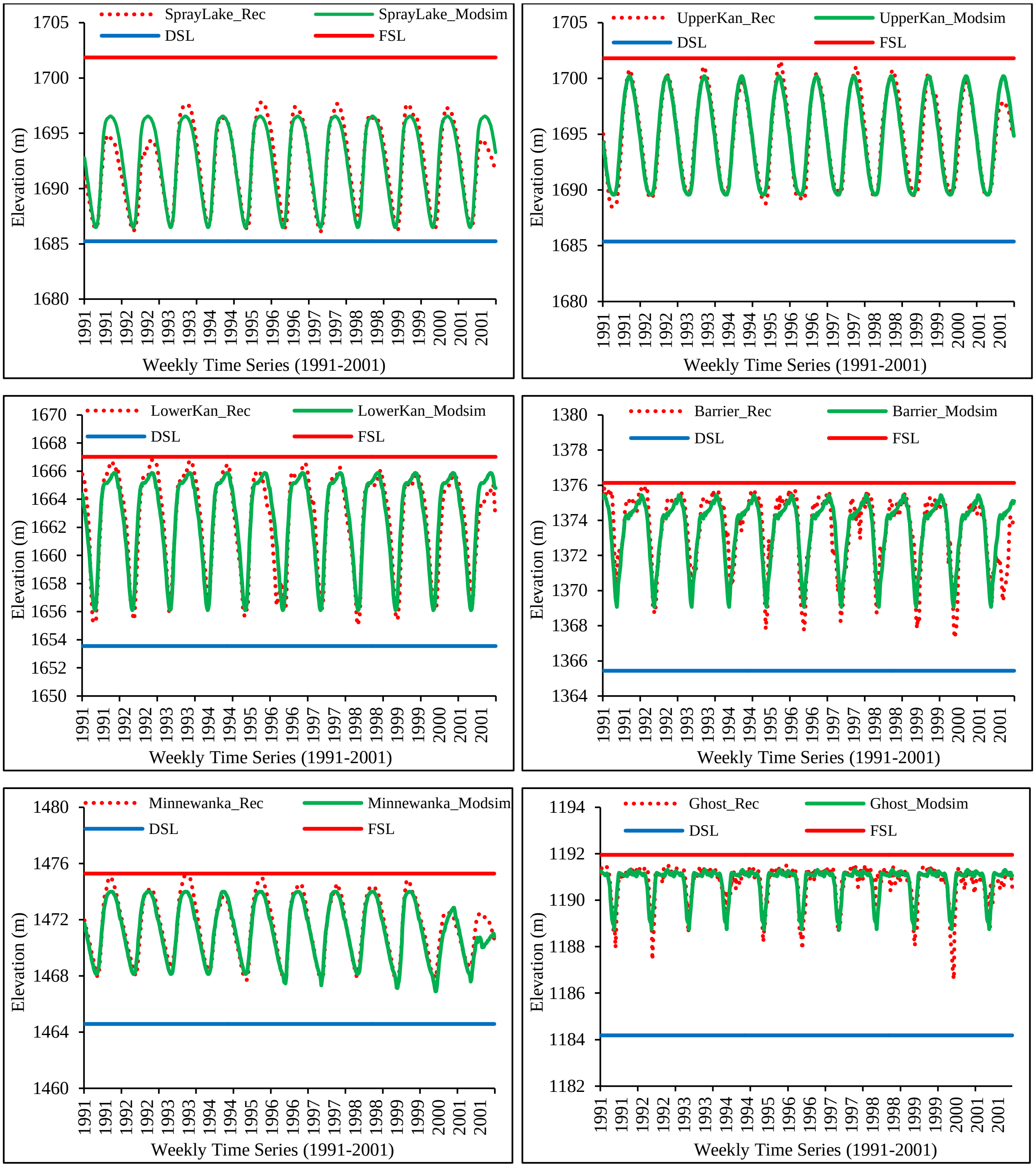

Figure C.8 MODSIM simulated elevation for different reservoirs of the TAU system

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Appendix D: Highwood River Diversion Plan (HRDP)

D.1 Introduction

The Highwood River Diversion Plan (HRDP) is used for water management in the Upper Highwood and Upper Little Bow river watersheds (Figure D.1). The water management history in this area started in 1898 with the first water diversions from the Highwood River to manage drought conditions in the Little Bow River basin. In 1933, a second diversion structure, Women's Coulee, was constructed, followed by many small storage sites. The objective of these diversions was to allow farmers and settlers to withstand droughts and maintain environmental stability. However, in later periods, the demand for irrigation and municipal use was increased rapidly, while low streamflow in the Highwood River was observed frequently, which put water users along the Little Bow River at risk (CEAA, 2019).

The Highwood River Public Advisory Committee (PAC) at that time was concerned about the water scarcity issues and endorsed a proposal to the Government of Alberta to capture the Highwood River water during high flow periods by increasing existing infrastructure capacity as well as building new structures and then releasing water to accommodate agricultural and other demands when flows are low. In 1996, based on the recommendation of the Highwood River PAC, the Alberta Public Works, Supply and Services (PWSS) applied with the Natural Resources Conservation Board to get an approval for construction of the Highwood River water diversion structure which is also known as the Little Bow Project (NRCB, 2019). Later, the proposal went through a joint federal-provincial review and modification processes and finally approved in 2008. In 2008, Alberta Environment published the approved water management operational plan report for the Highwood River diversion works (Alberta Environment, 2008c, 2008b) and using the WRMM model for water management and planning in this region.

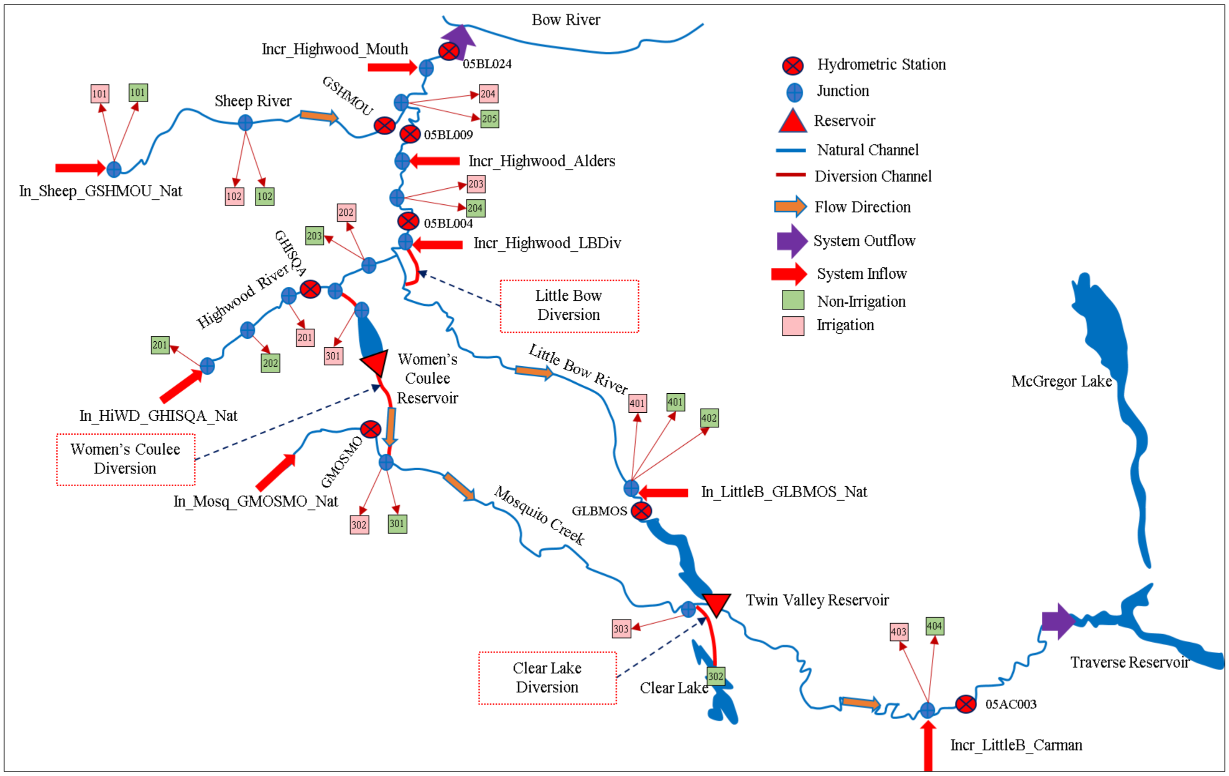

Figure D.1 The Highwood River Diversion Plan (HRDP) area located in the Upper Highwood and Upper Little Bow rivers

D.2 Reservoir Properties

D.2.1 General Properties

Table D.1 A summary of general information of the HRDP reservoirs

Reservoir Name	Twin Valley	Women's Coulee
MODSIM ID	R1_TwinVR	R2_WomenCR
First on Stream	2004	1933
Latitude	50.235443	50.524940
Longitude	-113.408518	-113.922597
Minimum Operating Level (m)	950	951
Maximum Operating Level (MOL) (m)	968	953.92
Storage Capacity (MCM)	64.12	0.36

Note:

- Reservoir elevation and capacity were collected from the watershed report of the Oldman River basin (Oldman Watershed Council, 2010) and the HRDP approved operational plan document (Alberta Environment, 2008b, 2008c)
- The location of the reservoirs was obtained manually from the Google Earth map

D.2.2 Reservoir Area-Capacity-Elevation (ACE)

Table D.2 Area (in square meter), Capacity (in cubic decameter) and Elevation (in meter) of the HRDP reservoirs

Twin Valley Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.0	0.0	946.0	3943987.0	19094.6	958.0
3424.0	3.4	947.0	4612731.0	23707.3	959.0
57820.0	61.2	948.0	5282234.0	28989.5	960.0
302799.0	364.0	949.0	5995865.0	34985.4	961.0
584675.0	948.7	950.0	6746774.0	41732.2	962.0
871116.0	1819.8	951.0	7515944.0	49248.1	963.0
1178098.0	2997.9	952.0	8353964.0	57602.1	964.0
1555456.0	4553.4	953.0	9337679.0	66939.7	965.0
1939279.0	6492.7	954.0	10391006.0	77330.8	966.0
2340601.0	8833.3	955.0	11328312.0	88659.1	967.0
2894464.0	11727.7	956.0	12337894.0	100997.0	968.0
3422839.0	15150.6	957.0			

Women's Coulee Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.0	0.0	950.0	84017.4	323.7	952.5
24266.8	93.5	950.5	93952.9	362.0	952.9
48533.7	187.0	951.0	101469.1	391.0	953.0
60361.6	232.6	951.5	148445.6	572.0	953.5
72189.5	278.1	952.0	187905.8	724.0	953.9
77393.8	298.2	952.2			

Note:

- Twin Valley Reservoir: Capacity and elevation were generated using the Canadian Digital Elevation Model (Natural Resources Canada, 2013). Area estimated considering the reservoir as a rectangular shape

➢ Women's Coulee Reservoir: Area, capacity, and elevation were generated manually using minimal data found in the reports available online. Dimensions generated using the Google Earth images and approximated as a cube rectangle

D.2.3 Reservoir Operating Policy

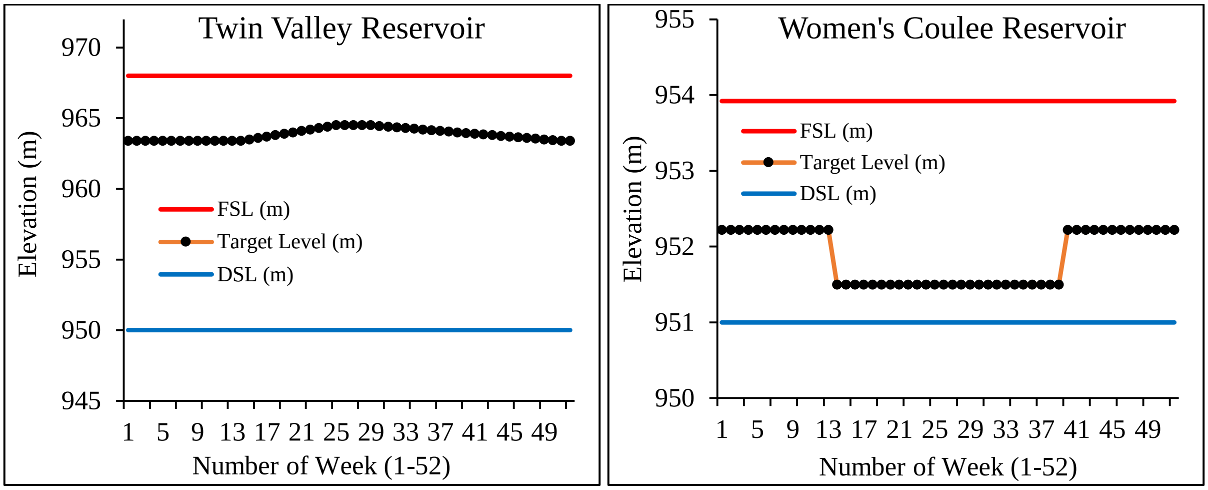

Figure D.2 Reservoir operating policy and storage capacity of the HRDP reservoirs

Note:

➢ The operational policy is not available for public access

➢ The Twin Valley Reservoir operating policy (target level) was derived based on mean weekly historical data (2004 to 2013), except 2008, due to the sparsity of recorded data

➢ The Women's Coulee Reservoir has tiny capacity comparatively other reservoirs, and reasonable operating policy was assumed to develop a model based on the downstream water diversion and management objectives

D.2.4 Reservoir Evaporation and Precipitation

Table D.3 Reservoir evaporation and precipitation considered in the HRDP model development

Reservoir	Evaporation Station	Weighting Factor	Precipitation Station	Weighting Factor
Twin Valley	Calgary	1.013	Calgary	0.920
Women's Coulee	Calgary	1.013	Calgary	0.943

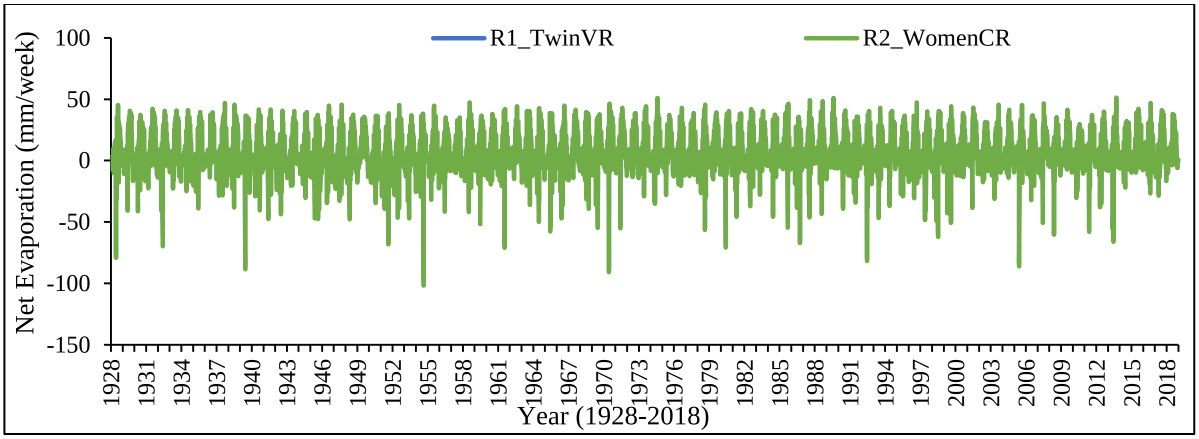

Figure D.3 Net reservoir evaporation considered for the HRDP reservoirs

D.3 Inflow Properties

Table D.4 Inflow properties considered in the HRDP model development

Sl.	Modsim Inflow Name	Inflow Type	Data Range	Inflow ID	MAI (MCM)
1	In_HiWD_GHISQA_Nat	Main	1928-2018	GHISQA	404.87
2	In_Sheep_GSHMOU_Nat	Main	1928-2018	GSHMOU	258.51
3	Incr_Highwood_LBDiv	Incremental	1928-2018	05BL004-GHISQA	4.40
4	Incr_Highwood_Alders	Incremental	1928-2018	05BL009-05BL004	31.63
5	Incr_Highwood_Mouth	Incremental	1928-2018	05BL024-05BL009-GSHMOU	5.38
6	In_Mosq_GMOSMO_Nat	Main	1928-2018	GMOSMO	18.50
7	In_LittleB_GLBMOS_Nat	Main	1928-2018	GLBMOS	5.99
8	Incr_LittleB_Carman	Incremental	1928-2018	05AC003-GLBMOS-GMOSMO	4.76

D.4 Channel Properties

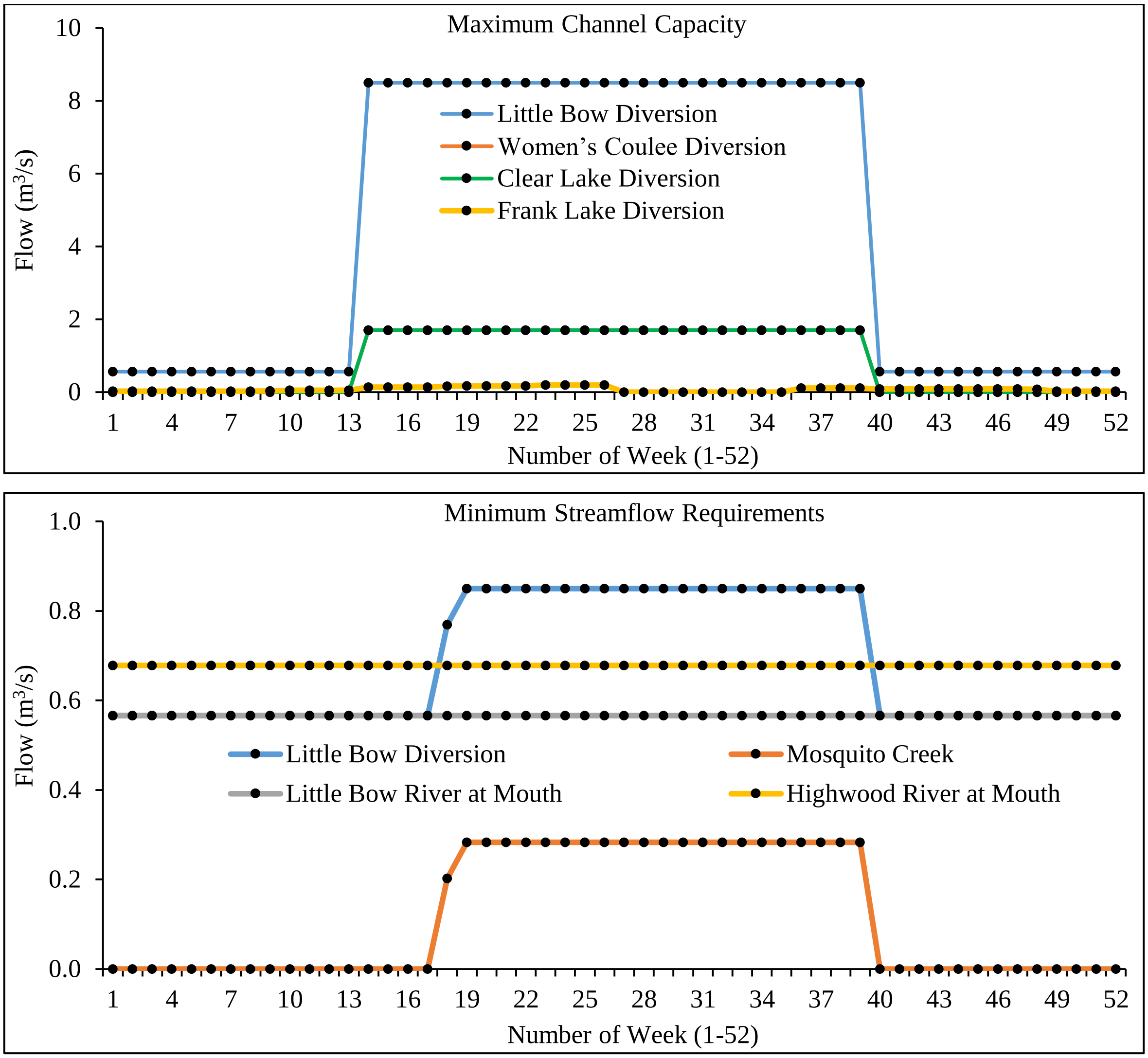

Figure D.4 Channel properties considered in the HRDP model development

Note:

- The minimum streamflow requirements (MSR) and maximum channel flow capacity were obtained from the Alberta Environment's Highwood River management plan documents (Alberta Environment, 2008b, 2008c)
- A large floating number, e.g., 1000 m^3/s, was considered as the maximum capacity of the Highwood, Sheep, and Little Bow Rivers

D.5 Demand Properties

Table D.5 Irrigation and non-irrigation demand in the HRDP area

Demand Type	MODSIM ID	Licensed Annual Demand (MCM)	Actual Demand Fraction
Irrigation	Irr_101	37005	0.8
Irrigation	Irr_102	334712	0.8
Irrigation	Irr_201	397180	0.8
Irrigation	Irr_202	1044644	0.8
Irrigation	Irr_203	1838197	0.8
Irrigation	Irr_204	18500	0.8
Irrigation	Irr_301	88810	0.8
Irrigation	Irr_302	1688776	0.8
Irrigation	Irr_303	1182004	0.8
Irrigation	Irr_401	5690545	0.8
Irrigation	Irr_403	39061574	0.8
Non-Irrigation	MW_101	97438	0.8
Non-Irrigation	MW_102	5154438	0.8
Non-Irrigation	MW_201	75243	0.8
Non-Irrigation	MW_202	1654096	0.8
Non-Irrigation	MW_203	1796071	0.8
Non-Irrigation	MW_204	1986409	0.8
Non-Irrigation	MW_205	17270	0.8
Non-Irrigation	MW_301	992996	0.8
Non-Irrigation	MW_402	2029256	0.8
Non-Irrigation	MW_404	482804	0.8
Special Diversion	MW_401_FrankL	4007900	0.35
Special Diversion	MW_302_ClearL	11160000	0.5

Note:

- All the irrigation (Irr) and non-irrigation (MW) licensed water demand in the HRDP area were obtained from the online portal of the Alberta Water Licence Viewer (Alberta

Environment, 2018b). Reasonable fraction values were considered to estimate the actual demand for the HRDP model development

- The non-irrigation demand at each week was obtained by dividing annual demand by 52 (1year =52 weeks)
- The irrigation demand at each week was obtained by multiplying annual demand by weekly demand fraction. The weekly demand fraction in the HRDP is assumed to be the same as adjacent Oldman River sub-basin irrigation demand, which was collected from the South Saskatchewan River Basin (SSRB) Database
- There are two unique demands, e.g., MW_401_FrankL and MW_302_ClearL, which are small natural ponds to support environmental, recreational, and irrigation activities. However, this study considered them as a demand node, not as a reservoir due to the unavailability of sufficient data

D.6 Priority System

Table D.6 The system priority of the HRDP water management model

Name of the Component	Node Type	MODSIM Priority	Note
FT_HWMouth	MSR	1	Highwood River at Mouth
FT_ToTraverse	MSR	1	Little Bow River at Mouth
FT_MosqCr	MSR	2	Mosquito Creek
FT_UpLittleB	MSR	2	Little Bow Diversion
Major withdrawal nodes	Demand	3	Non-Irrigation (MW)
Irrigation nodes	Demand	4	Irrigation (Irr)
R2_WomenCR	Reservoir	5	Women's Coulee Reservoir
R1_TwinVR	Reservoir	6	Twin Valley Reservoir
MW_302_ClearL	Special Diversion	7	Non-Irrigation
MW_401_FrankL	Special Diversion	8	Non-Irrigation

Note: The priority of demand (irrigation, non-irrigation, and especial diversion), MSR, reservoir operations were obtained from Alberta Environment’s HRDP operational plan (Alberta Environment, 2008c, 2008b).

D.7 HRDP Schematic in MODSIM Graphical User Interface (GUI)

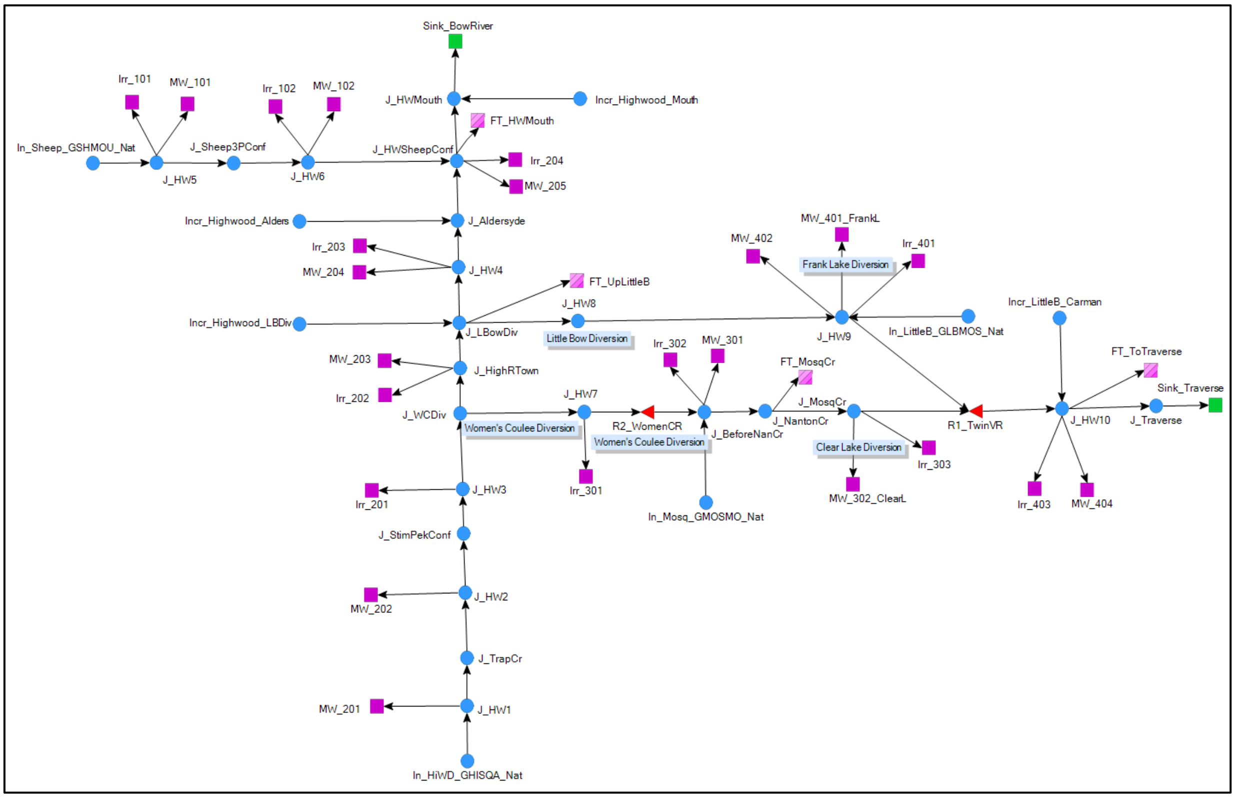

Figure D.5 The HRDP schematic diagram in MODSIM GUI

D.8 Model Validation and Results

Table D.7 Water balance of the developed HRDP model

Category	HRDP
Inflow from rivers (MCM)	13.510
Outflow to downstream (MCM)	12.314
Allocation to demand (MCM)	1.136
Reservoir storage gain (+) / loss (-) (MCM)	-0.000015
Reservoir evaporation (MCM)	0.082
Reservoir precipitation (MCM)	0.022
Return flow (MCM)	0.000
Total available water (MCM)	13.532
Total outflow (MCM)	13.532
Difference (MCM)	0.000
Error (%)	-0.0020%

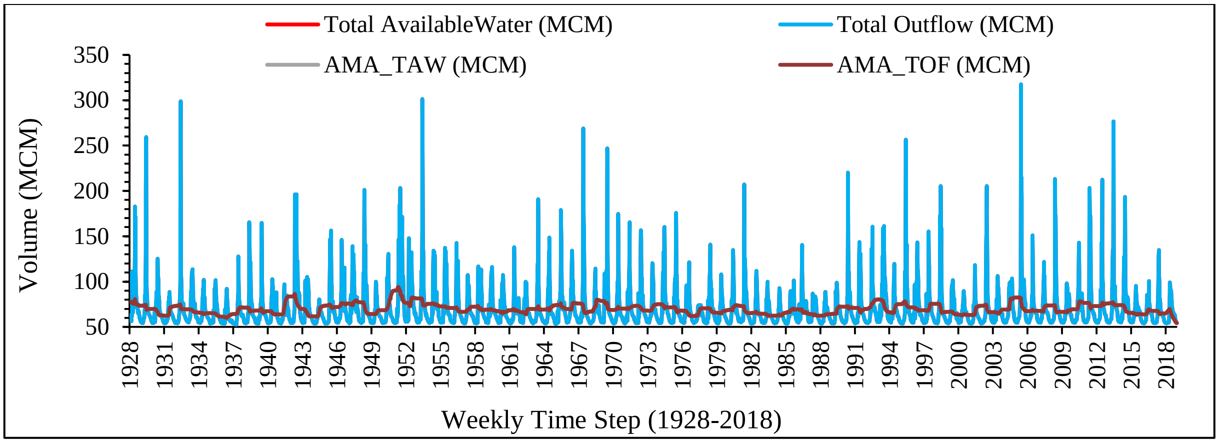

Figure D.6 Water balance of the developed HRDP model for weekly time step and respective annual moving average (AMA)

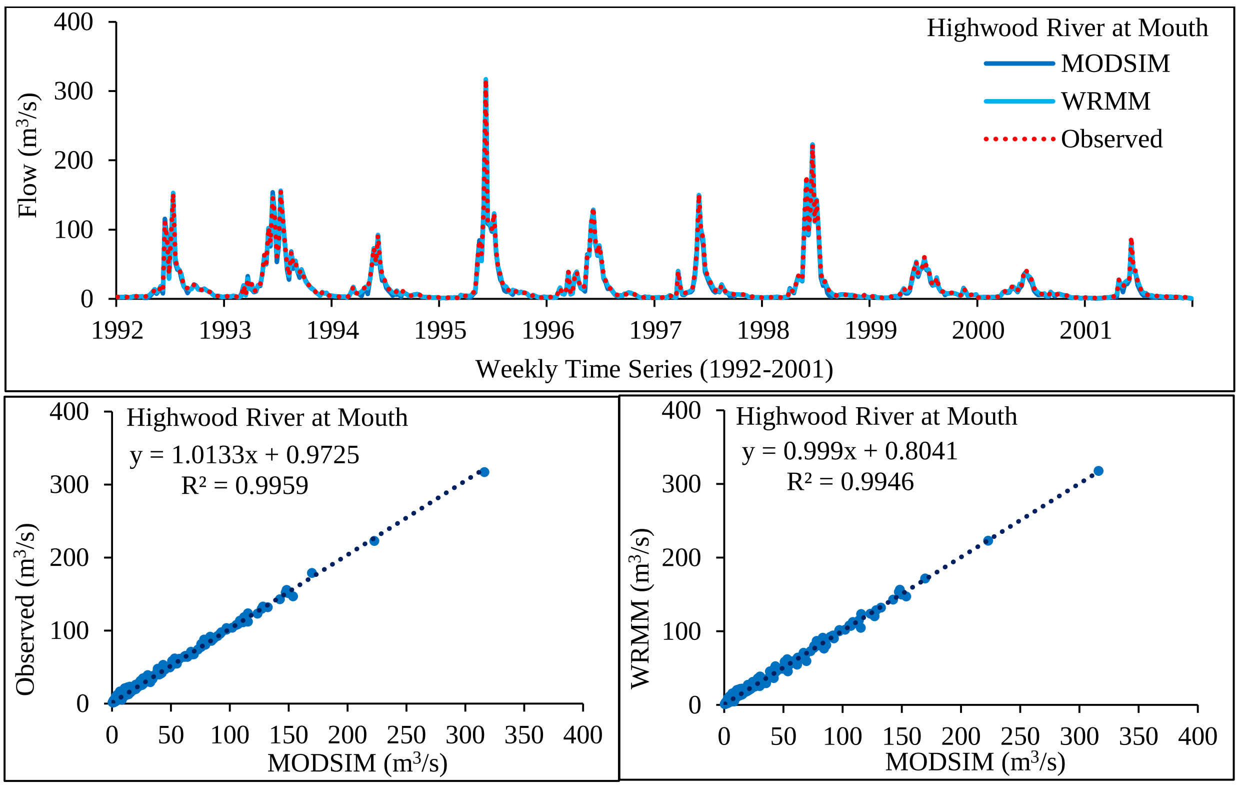

Figure D.7 Outflow from the HRDP model to the Bow River

D.9 References

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Appendix E: Southern Tributaries (STRIBS)

E.1 Introduction

The Southern Tributaries (STRIBS) is an extensive water management sub-system located in southwestern Alberta and delivers irrigation water supply by connecting all three southern tributaries of the Oldman River, e.g., Waterton, Belly, and St. Mary, which in turn a tributary of the South Saskatchewan River (SSR). The initial development of this system started in the late 1890s, evolved and operated by different administrations (Klassen and Gilpin, 1999). In 1950, the Prairie Farm Rehabilitation Administration (PFRA) started the construction and operation of the St. Mary and Waterton reservoirs, including the Belly River diversion works and connecting other canals (Alberta Agriculture, 2004). Significant development has taken place between 1970 and 1980, which involves irrigation expansion and modern infrastructure development. In 2001, the Alberta Agriculture and Forestry developed a water allocation and forecasting model, using Microsoft Excel software to determine the availability of water and possible diversion to different irrigation users of the STRIBS area (Healy, 2015). Since then, the model has been used to provide water allocation forecast, especially in times of drought for the irrigation users of this system. Besides, the Alberta Environment and Parks is also using the WRMM model for long term water management planning in this region.

The STRIBS system consists of both irrigation districts and private irrigation projects, which consume 96% of the water of the watershed (Alberta Agriculture, 2004). There are eight among thirteen irrigation districts of Alberta located in this region, which involves Mountain View Irrigation District (MVID), Leavitt Irrigation District (LID), Aetna Irrigation District (AID), United Irrigation District (UID), Magrath Irrigation District (MID), Raymond Irrigation District (RID), Taber Irrigation District (TID), and St. Mary River Irrigation District (SMRID), covering a total of 565,809 acres of land in the system (Figure E.1).

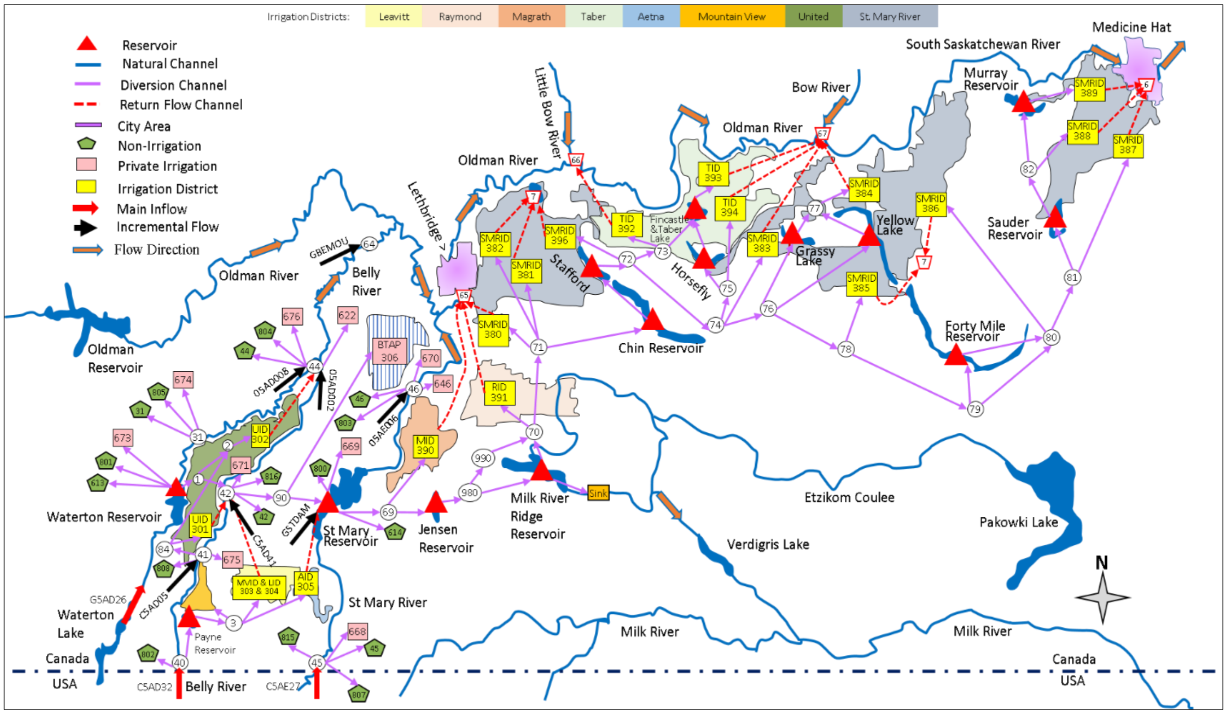


Figure E.1 Water resources system diagram of the Southern Tributaries (STRIBS) located in the southern part of the Oldman River, Alberta (Government of Alberta, 2019b)

The SMRID is the largest irrigation district in the STRIBS area as well as in Canada and utilizes water from the St. Mary Reservoir, which is the largest irrigation supply reservoir in Alberta, located on the St. Mary River. Private irrigation projects involve the Blood Tribe Agriculture Project (BTAP), covering 25,000 acres of land and other private irrigation projects covering more than 21,000 acres of land. The Blood Tribe Irrigation Project holds the largest private license in the province of Alberta, irrigates on the Blood reserve for non-aboriginal leaseholders, and is a key source of economic activity for the Blood Tribe (Government of Alberta, 2019c). Apart from the irrigation, there are 15 communities with an estimated population of 25,000, which depends on the STRIBS water supply for municipal and other purposes. Also, there is an International Water Sharing Agreement that exists in this system between Canada and the US. According to the 1921 Order of the International Joint Commission (IJC), "Canada receives 75% of the first 18.86 m^3/s of the natural flow of the St. Mary River at the international boundary and 50% of any excess over 18.86 m^3/s during the irrigation season" (Alberta Environment, 2019).

E.2 Reservoir Properties

E.2.1 General Properties

Table E.1 Existing reservoirs of the STRIBS water resource system

Sl.	Reservoir Name	Date of Impoundment	On/Off Stream	Licensee	Licensed Purpose
1.	Waterton	1965	On	GoA	Multipurpose
2.	St. Mary	1951	On	GoA	Multipurpose
3.	Payne Lake	1942	Off	GoA	Multipurpose
4.	Jensen	1948	On	GoA	Multipurpose
5.	Milk River Ridge	1957	Off	GoA	Multipurpose
6.	Chin	1954	Off	SMRID	Irrigation
7.	Stafford	1954	Off	SMRID	Irrigation
8.	Sherburne (Grassy)	1952	Off	SMRID	Irrigation
9.	Yellow Lake	1952	Off	SMRID	Irrigation
10.	Forty Mile	1987	Off	SMRID	Irrigation
11.	Sauder (Rattlesnake)	1953	Off	SMRID	Irrigation
12.	Murray	1954	On	SMRID	Irrigation
13.	Fincastle & Taber	1952 & 1955	Off	TID	Irrigation
14.	Horsefly	1950	Off	TID	Irrigation

Table E.2 STRIBS reservoirs location and storage capacity

Sl.	Reservoir Name	Latitude	Longitude	DSL (m)	FSL (m)	Storage Capacity (MCM)
1.	Waterton	49.308452	-113.674777	1170.59	1185.7	114
2.	St. Mary	49.32592	-113.191389	1078.56	1103.6	369
3.	Payne Lake	49.112405	-113.656777	1342.62	1343.6	9
4.	Jensen	49.314001	-112.898553	1058.31	1072.64	19
5.	Milk River Ridge	49.366563	-112.51817	1028.2	1032.4	112
6.	Chin	49.616182	-112.222974	854.7	864.1	190
7.	Stafford	49.734836	-112.46152	841.58	846.6	22
8.	Sherburne (Grassy)	49.755788	-111.785718	808.275	809.9	12
9.	Yellow Lake	49.735912	-111.501408	782	784	18
10.	Forty Mile	49.649167	-111.397037	809.58	813	86
11.	Sauder (Rattlesnake)	49.977231	-111.000979	802.04	804	38
12.	Murray	49.809487	-110.946051	765.4	766.6	31
13.	Fincastle & Taber	49.805378	-112.09322	793	795.5	10
14.	Horsefly	49.72179	-112.079327	819.50	820.80	8

Note:

- The general properties of the STRIBS reservoirs, such as the date of impoundment and license information, were collected from the Government of Alberta's online portal (AMEC, 2014; Government of Alberta, 2015)
- The reservoir location was obtained by manual search using the Google Earth software package
- The historical weekly mean elevation of the STRIBS reservoirs was obtained from the South Saskatchewan River Basin Weekly Natural Flow Database (SSRB Database), Environment Canada's Hydrometric Database (HYDAT) (WSC, 2019) and the online portal of Alberta River Basins (Alberta Environment, 2018a)
- The dead storage level (DSL) and full supply level (FSL) of reservoirs were derived based on the historical minimum and maximum elevation of the reservoirs, respectively. Many reservoirs capacity was expanded over time, which eventually raised the reservoir's minimum elevation. This study considered reservoir DSL and FSL after reservoir capacity extension. The difference of storage at DSL and FSL was considered as the storage capacity of the STRIBS reservoirs and also compared with literature (AMEC, 2014) for credibility assessment of collected data

E.2.2 Reservoir Area-Capacity-Elevation (ACE)

The Area-Capacity-Elevation data for the Waterton and St. Mary reservoirs were collected from the SSRB Database. For other reservoirs, this study used the Bathymetry Maps adopted from the web resources of the Government of Alberta (Government of Alberta, 2019a). Some of the reservoirs Bathymetry maps were not available, e.g., Yellow Lake, Murray Lake, Taber Lake, and Horsefly Reservoir, and this study collected information from the online portal of Alberta River Basins (Alberta Environment, 2018a). The ACE, which was used to develop a water management model for the STRIBS, is summarized in Table E.3.

Table E.3 Area (in square kilometer), Capacity (in cubic decameter) and Elevation (in meter) of the STRIBS's reservoirs

Waterton Reservoir (Station ID: 05AD026)					
Area	Capacity	Elevation	Area	Capacity	Elevation
5.09	0.00	1170.59	9.23	83389.53	1182.62
5.97	15885.48	1173.48	10.91	114072.22	1185.67
6.88	35467.35	1176.53	10.92	114418.00	1185.7
7.67	57640.03	1179.58	12.16	149226.33	1188.72

St. Mary Reservoir (Station ID: 05AE025)					
Area	Capacity	Elevation	Area	Capacity	Elevation
3.47	0.00	1078.56	15.90	133850.19	1094.23
3.56	1065.89	1078.99	20.64	189541.89	1097.28
5.10	14264.14	1082.04	27.11	262317.31	1100.33
7.28	33136.41	1085.09	37.31	360502.46	1103.38
9.43	58607.81	1088.14	38.06	369304.00	1103.60
12.02	91295.07	1091.18	42.49	421313.11	1104.90

Payne Lake					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.00	0.00	1337.54	1.80	6384.96	1342.49
0.56	1416.24	1338.58	1.83	6607.74	1342.62
0.96	2129.72	1339.50	1.88	7007.00	1342.83
1.15	2718.03	1340.05	1.94	7417.83	1343.04
1.30	3322.86	1340.54	2.03	8027.29	1343.35
1.56	4731.27	1341.51	2.22	8162.77	1343.41
1.69	5529.70	1342.00	2.24	8703.00	1343.60

Jensen Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.41	0.00	1056.86	1.16	6551.04	1065.36
0.46	311.21	1057.58	1.32	8025.83	1066.54
0.53	778.38	1058.53	1.46	9356.08	1067.49
0.58	1044.86	1059.00	1.54	10180.00	1068.02
0.63	1335.24	1059.47	1.59	10820.14	1068.43
0.71	1972.65	1060.41	1.69	12377.25	1069.37
0.78	2679.22	1061.36	1.77	13608.92	1070.08
0.87	3656.50	1062.54	1.82	14459.85	1070.55
0.96	4524.76	1063.48	1.86	15649.05	1071.15
1.07	5492.70	1064.42	2.02	18749.00	1072.64

Milk River Ridge Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
3.13	0.00	1019.39	10.03	52350.06	1027.50
3.47	653.33	1019.58	10.87	63704.58	1028.58
4.15	4152.58	1020.48	11.59	73878.39	1029.48
4.80	9044.83	1021.56	12.05	80301.45	1030.02
5.42	13680.39	1022.46	12.54	86987.17	1030.56
5.83	16752.21	1023.00	12.98	93917.96	1031.10
6.28	20063.77	1023.54	13.38	101073.25	1031.64
7.03	26132.50	1024.44	13.53	102197.00	1031.72
7.92	34245.37	1025.52	13.70	103540.01	1031.82
8.98	41960.53	1026.42	14.52	111500.00	1032.40

Chin Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
6.84	0.00	846.23	13.37	92667.16	854.70
7.67	2417.96	846.60	13.75	104914.35	855.60
8.71	9933.15	847.50	14.12	117496.08	856.50
9.61	18278.45	848.39	14.39	127146.00	857.17
10.56	29752.81	849.52	14.74	140289.88	858.07
11.17	39605.05	850.42	15.00	150358.21	858.75
11.60	47339.98	851.10	15.19	157171.37	859.20
11.86	52650.03	851.54	15.45	167542.07	859.87
12.11	58071.31	852.00	15.53	171036.00	860.10
12.34	63597.29	852.45	15.69	174565.60	860.32
12.77	74947.37	853.35	22.65	190300.00	864.10
13.08	83707.54	854.02			

Stafford Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.76	0.00	840.69	4.08	11151.65	844.55
1.60	353.85	841.01	4.33	13174.90	845.03
2.26	1505.98	841.58	4.58	15317.81	845.50
2.60	2687.15	842.06	4.88	18045.99	846.08
2.92	4021.31	842.54	5.02	19474.16	846.36
3.25	5510.66	843.02	5.14	19965.99	846.46
3.51	7141.83	843.50	5.18	21500.00	846.60
3.72	8593.00	843.88			

Sherburne (Grassy) Lake					
Area	Capacity	Elevation	Area	Capacity	Elevation
2.89	0.00	806.48	3.31	4064.59	807.79
2.89	16.77	806.49	3.37	4611.37	807.95
2.94	493.24	806.65	3.43	5168.30	808.11
2.98	977.62	806.81	3.49	5735.29	808.27
3.03	1470.08	806.97	3.56	6312.33	808.44
3.09	1970.92	807.14	3.62	6899.68	808.60
3.14	2480.38	807.30	3.78	7143.00	808.66
3.20	2999.05	807.46	4.07	7559.52	808.76
3.25	3527.16	807.62	7.25	12100.00	809.90

Yellow Lake					
Area	Capacity	Elevation	Area	Capacity	Elevation
1.36	6499.35	782.00	2.39	11426.42	783.10
1.43	6841.42	782.10	2.52	12027.81	783.20
1.51	7201.50	782.20	2.65	12660.86	783.30
1.59	7580.52	782.30	2.79	13327.22	783.40
1.67	7979.50	782.40	2.94	14028.65	783.50
1.76	8399.47	782.50	3.10	14767.00	783.60
1.85	8841.55	782.60	3.26	15544.21	783.70
1.95	9306.89	782.70	3.43	16362.33	783.80
2.05	9796.73	782.80	3.61	17223.50	783.90
2.16	10312.35	782.90	3.80	18130.00	784.00
2.28	10855.10	783.00			

Forty Mile Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
3.81	0.00	797.10	5.81	51345.73	807.54
3.91	1527.99	797.50	5.94	56018.14	808.33
4.15	5818.08	798.55	5.98	57597.79	808.59
4.33	9202.33	799.35	6.12	62408.98	809.39
4.56	13927.10	800.40	6.30	68992.89	810.44
4.77	18887.51	801.46	6.49	75775.92	811.50
4.99	24072.93	802.52	6.59	79243.64	812.03
5.18	29467.72	803.56	6.60	79708.00	812.10
5.31	33640.94	804.37	6.68	82759.51	812.56
5.48	39365.52	805.42	6.75	84542.24	812.82
5.65	45268.66	806.48	6.77	86340.00	813.00

Sauder (Rattlesnake)					
Area	Capacity	Elevation	Area	Capacity	Elevation
3.44	0	798.76	9.56	25163	802.67
4.00	2148	799.35	9.83	26886	802.85
5.32	6134	800.18	9.89	27219	802.88
6.68	11258	801.01	10.71	29446	803.09
8.90	21253	802.26	15.22	37795	804.00
9.23	23173	802.47	17.35	40695	804.30

Murray Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.00	0.04	764.36	4.23	20046.00	765.87
2.35	11139.63	765.20	4.23	20073.00	765.87
2.49	11802.49	765.25	4.29	20348.00	765.89
2.63	12465.34	765.30	4.30	20375.00	765.90
2.77	13128.20	765.35	4.31	20460.00	765.90
2.91	13791.06	765.40	4.33	20542.00	765.91
3.05	14453.92	765.45	4.38	20756.00	765.92
3.19	15116.78	765.50	4.64	22000.00	766.00
3.35	15900.00	765.55	4.98	23600.00	766.10
3.44	16300.00	765.60	6.50	30825.00	766.60

Fincastle & Taber Lake					
Area	Capacity	Elevation	Area	Capacity	Elevation
1.22	0.00	791.83	3.36	4065.81	793.90
1.36	158.02	791.99	3.67	4624.23	794.08
1.53	388.78	792.16	4.09	5446.03	794.31
2.05	1240.42	792.70	4.51	6355.18	794.55
2.36	1824.81	793.00	5.13	7883.02	794.91
2.65	2487.75	793.30	5.60	8449.53	795.03
3.04	3388.37	793.66	6.36	10180.00	795.50
3.12	3551.49	793.72			

Horsefly Reservoir					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.00	0.00	819.26	5.11	4898.00	820.16
1.38	1320.87	819.50	7.03	6747.07	820.50
4.20	4033.97	820.00	8.16	7832.32	820.70
5.06	4852.00	820.15	8.73	8375.00	820.80

E.2.3 Reservoir Operating Policy

The Waterton and St. Mary reservoirs are the central water management infrastructure in the STRIBS, while others mainly used for irrigation purposes. For model development and reservoir operation, this study collected historical weekly mean elevation of the Waterton and St. Mary reservoirs for a different range of periods, and then considered the weekly minimum, maximum and average elevation of the respective reservoirs for ten years (1992-2001) as target operating policy of those reservoirs (Figure E.2). For other reservoirs, daily water level was collected from the online portal of Alberta River Basins (Alberta Environment, 2018a) and HYDAT database, and then estimated weekly elevation. The average observed level was considered as the target elevation for those reservoirs. No recorded elevation was found for the Fincastle, Taber, and Yellow Lake, and therefore, this study assumed the same operating policy of the Horsefly and Sherburne (Grassy) Lake for them, respectively. The operating policy considered in this study for different reservoirs of the STRIBS model development is presented in Figure E.2 and Figure E.3.

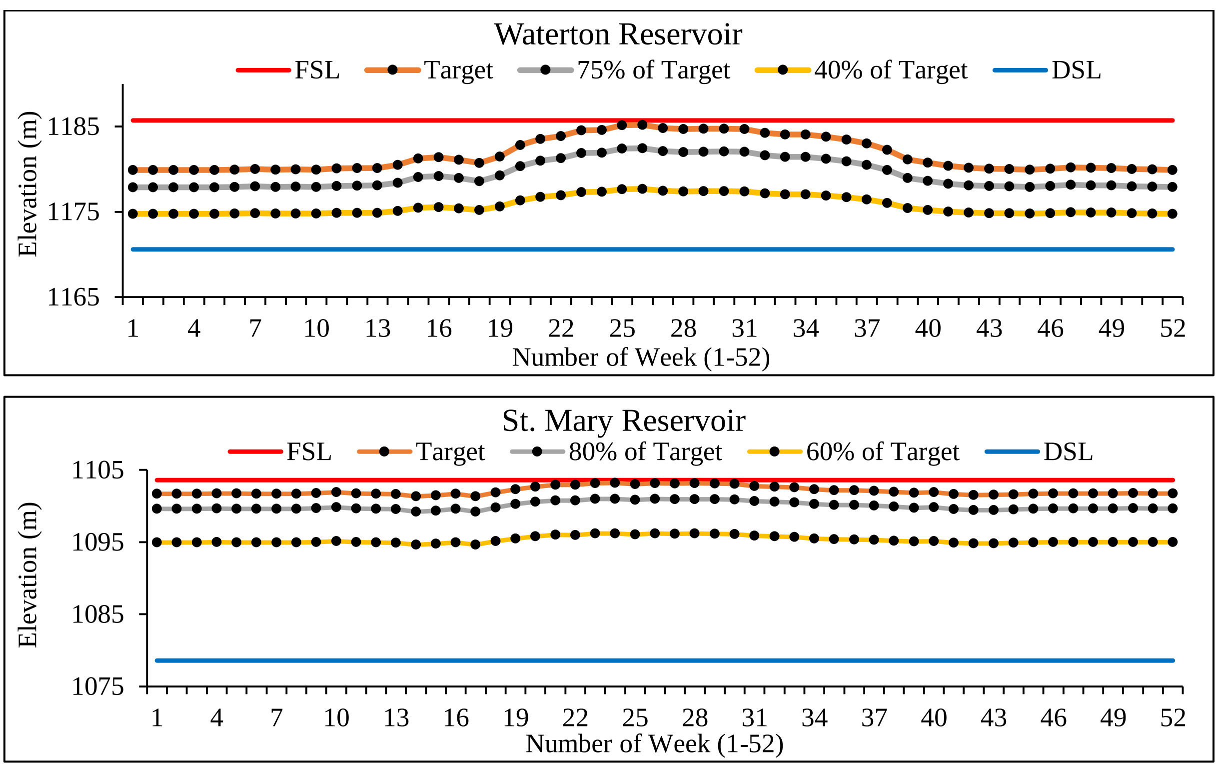


Figure E.2 Operating policy of the Waterton and St. Mary reservoirs considered in STRIBS model development

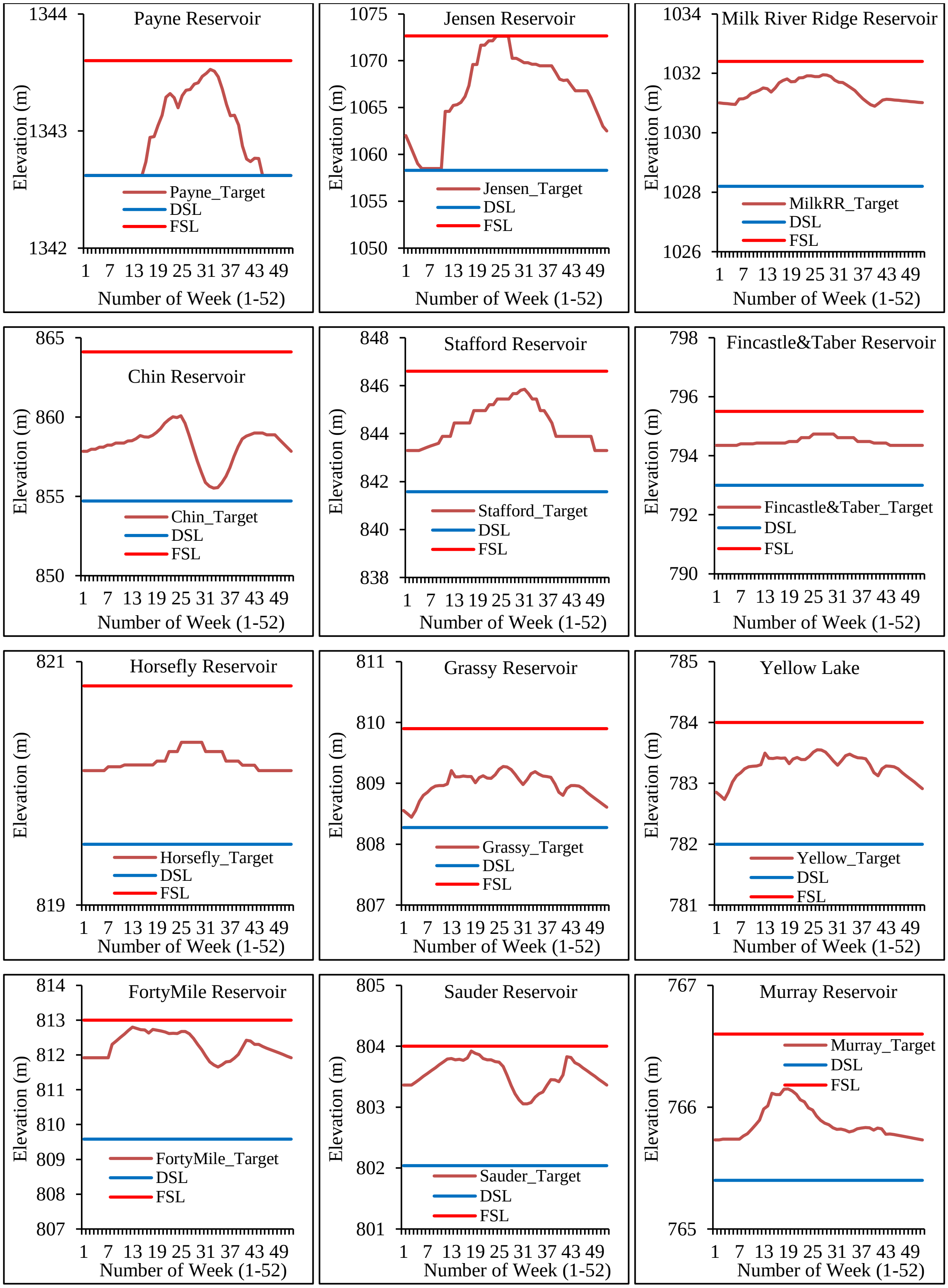


Figure E.3 Operating policy of different reservoirs considered in STRIBS model development

E.2.4 Reservoir Evaporation and Precipitation

The evaporation and precipitation data at nearby stations of the STRIBS reservoirs were adopted from the SSRB Weekly Database and the WRMM Alberta model, respectively. The map of isohyetals of mean annual precipitation and evaporation for the South Saskatchewan River basin were used to adjust those collected data for individual reservoirs. A weighting factor was used in the adjustment process, which can be defined as the ratio of annual precipitation and evaporation in the STRIBS reservoir sites to those of collected data sites. The ratio used in this study is presented in Table E.4 below. Net evaporation at each reservoir site was estimated by subtracting the weekly precipitation from corresponding weekly lake evaporation (Figure E.4). Negative net evaporation for a week indicates that the precipitation amount exceeded the evaporation amount for that week.

Table E.4 Evaporation and Precipitation station along with the weighting factor considered for the STRIBS reservoirs

MODSIM ID	Reservoir Name	Evaporation Station	Weighting Factor	Precipitation Station	Weighting Factor
R_206	Waterton	Calgary	1.038	Calgary	1.32
R_208	St. Mary	Calgary	1.070	Calgary	1.08
R_207	Paine	Calgary	1.042	Calgary	1.30
R_210	Jensen	Calgary	1.089	Calgary	1.06
R_209	Milk River Ridge	Calgary	1.091	Calgary	1.02
R_270	Chin	Calgary	1.091	Calgary	0.85
R_271	Stafford	Calgary	1.089	Calgary	0.87
R_272	Fincastle & Taber	Calgary	1.085	Calgary	0.81
R_273	Horsefly R	Calgary	1.087	Calgary	0.81
R_274	Grassy	Calgary	1.087	Calgary	0.87
R_275	Yellow	Calgary	1.084	Calgary	0.94
R_276	Forty Mile	Calgary	1.091	Calgary	0.88
R_277	Sauder	Calgary	1.082	Calgary	0.87
R_278	Murray	Calgary	1.078	Calgary	0.87

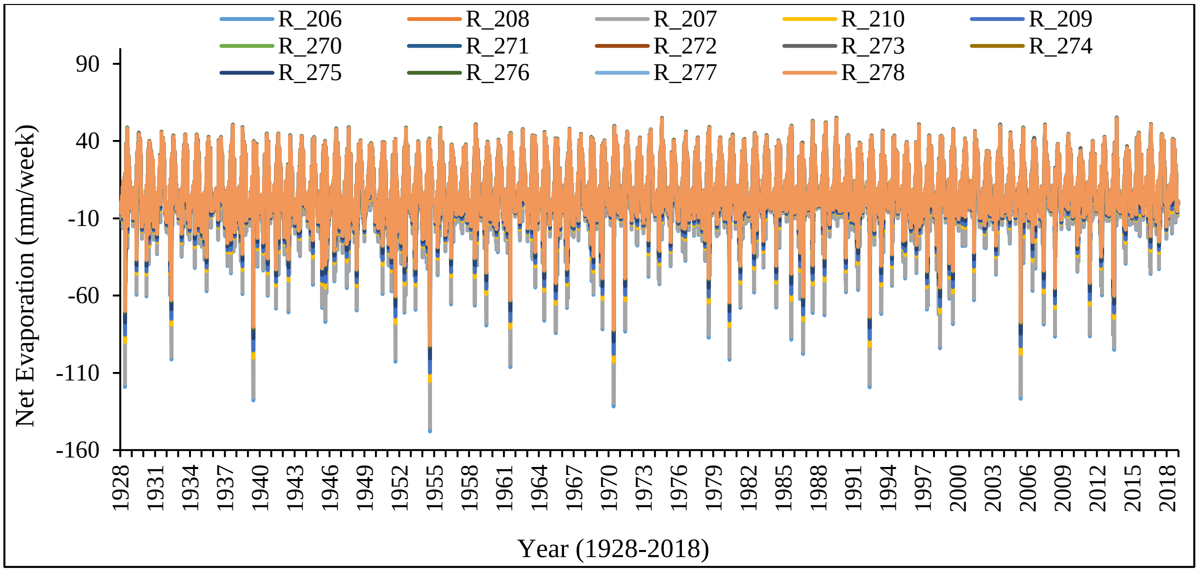


Figure E.4 Net reservoir evaporation estimated based on the evaporation and precipitation at Calgary station, adopted from the WRMM, Alberta

E.3 Inflow Properties

Table E.5 Inflow properties considered in the STRIBS water resource system

Sl.	MODSIM Inflow Name	Inflow Type	Inflow ID	MAI* (MCM)
1	In_05AD026_Wat	Main	05AD026	691.9
2	In_05AD032_Bel	Main	05AD032	220.8
3	In_05AD027_StM	Main	05AE027	759.1
4	Incr_05AD005_BelMV	Incremental	05AD005-05AD032	81.6
5	Incr_05AD041_BelGlen	Incremental	05AD041-05AD005	19.7
6	Incr_05AD002_BelSO	Incremental	05AD002-05AD041	33.6
7	Incr_05AD008_WatSO	Incremental	05AD008-05AD026	58.3
8	Incr_GSTDAM_StDam	Incremental	GSTDAM-05AD027	81.6
9	Incr_05AE006_StLethB	Incremental	05AE006-GSTDAM	24.1

Note:

- The Waterton, Belly, and St. Mary Rivers are the primary sources of surface water in the STRIBS area

- Incremental flows were considered at critical locations throughout the downstream based on the cumulative naturalized streamflow data to include local runoff contribution in the system
- Naturalized streamflow data were obtained from the SSRB Database (1928-2001) and extended until 2018 after converting available gauge data to naturalized data

E.4 Channel Properties

To satisfy minimum streamflow requirements (MSR) and avoid flooding in the downstream, minimum and maximum capacity were attached with each natural and diversion channel during STRIBS model development. The natural channel properties were adopted from the existing water management model of the SSRB, Alberta, e.g., WRMM, and for diversion channels, historical minimum and maximum values were considered as the capacity of respective channels. The recorded data were obtained from the SSRB Database and HYDAT Database. To safely run the developed model, this study assumed a large floating number as maximum capacity for channels whose capacity was not available. A summary of channel properties considered in the STRIBS model development is presented in Table E.6 and Figure E.5 below.

Table E.6 Channel properties considered for the STRIBS model development

Channel Name	MSR (m^3/s)	Maximum Capacity (m^3/s)	Reference
Waterton River: Reservoir to Stand Off	2.27	2000	WRMM, Alberta
Belly River: International Boarder to Mountain View	0.1	2000	WRMM, Alberta
Belly River: Mountain View to Glenwood	0.85	2000	WRMM, Alberta
Belly River: Glenwood to Stand Off	0.93	2000	WRMM, Alberta
Belly River: Waterton-Belly Confluence to near the Mouth	0.93	2000	WRMM, Alberta
St. Mary River: International boundary to Stand Off	0	2000	WRMM, Alberta
St. Mary River: Stand Off to near Lethbridge	2.75	2000	WRMM, Alberta
MVID Diversion from Belly River	0	4.6	Station ID # 05AD017
SMRID diversion from St. Mary River	0	91.6	Station ID # 05AE300
UID diversion from Belly River	0	7.9	Station ID # 05AD013
Waterton to Belly Diversion Canal	0	55	Station ID # 05AD027
UID Diversion from Waterton-Belly Diversion Canal	0	2.1	Station ID # 05AD413
Belly to St. Mary River Diversion Canal	FT_476	68.4	Station ID # 05AD021
All other channels	0	1000	Large floating number

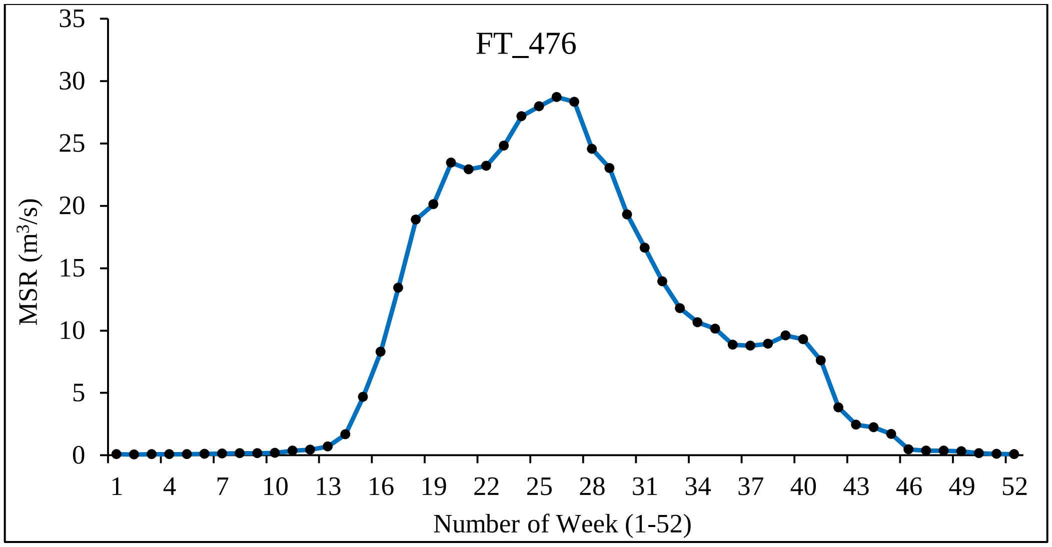
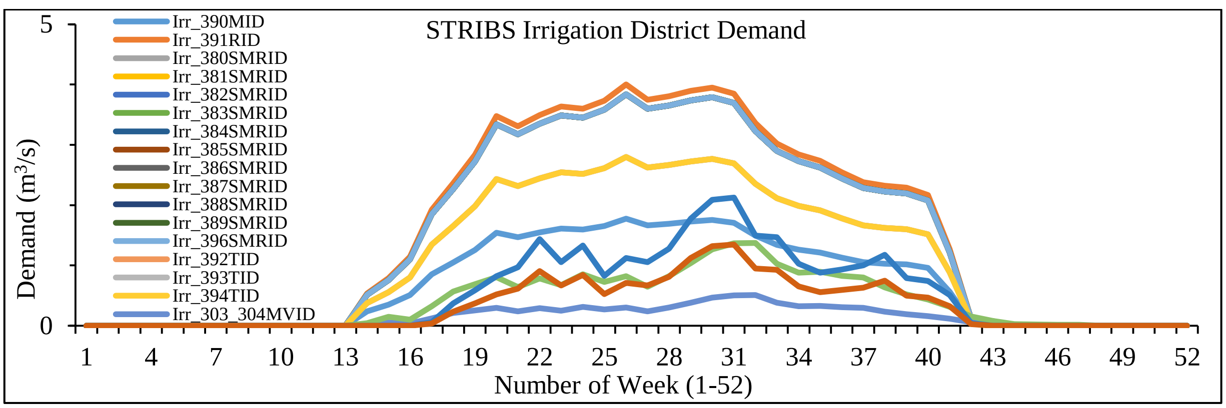


Figure E. 5 Minimum streamflow requirements (MSR) in the STRIBS system

E.5 Demand Properties



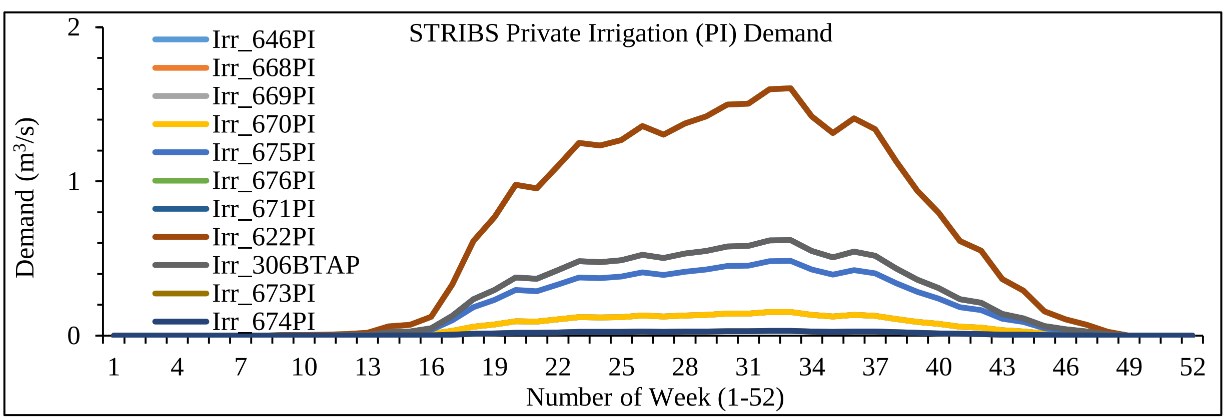


Figure E.6 Irrigation district (top) and private irrigation (bottom) demand in the STRIBS area

Table E.7 Annual non-irrigation demand in the STRIBS area

Demand Type	MODSIM ID	Annual Demand (MCM)
Non-Irrigation	MW_800	9.74
Non-Irrigation	MW_803	9.74
Non-Irrigation	MW_815	9.74
Non-Irrigation	MW_614	9.74
Non-Irrigation	MW_45	9.74
Non-Irrigation	MW_46	9.74
Non-Irrigation	MW_802	0.02
Non-Irrigation	MW_808	0.02
Non-Irrigation	MW_804	1.13
Non-Irrigation	MW_816	0.82
Non-Irrigation	MW_42	0.82
Non-Irrigation	MW_44	1.13
Non-Irrigation	MW_801	1.13
Non-Irrigation	MW_805	1.13
Non-Irrigation	MW_613	1.13
Non-Irrigation	MW_31	1.13

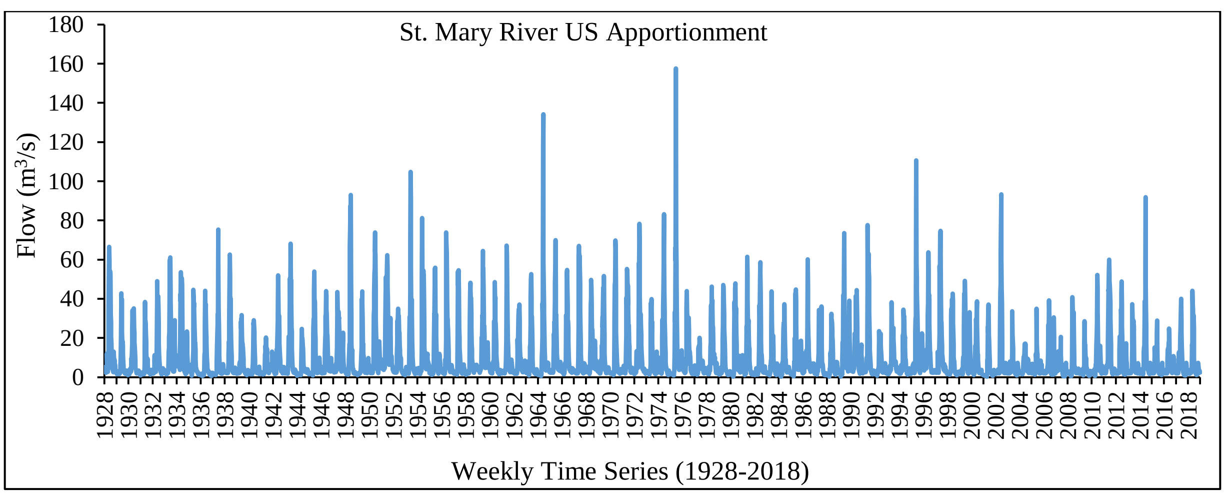


Figure E.7 The US apportionment of the St. Mary River at the US-Canada border

E.6 Return Flow Properties

All return flows in the STRIBS are coming from different irrigation districts. Return flow properties, e.g., source of return flow, return location, and the fraction of return flow with respect to the gross diversion was obtained from the existing water management model of the SSRB, Alberta, and the SSRB Database. The return flow channels and associated return flow fraction, which were incorporated into this study, are briefly explained in Table E.8 below.

Table E.8 Irrigation return flow in the STRIBS system

User Reference No	Irrigation District	Return Flow Location	Return Flow Fraction
UID 301	UID	Belly River near Glenwood (Junction 42)	0.52
UID 302	UID	Belly-Waterton Confluence (Junction 44)	0.52
MVID 303 and LID 304	MVID	Belly River near Glenwood (Junction 42)	0.55
AID 305	MVID	St. Mary Reservoir	0.55
MID 390	SMRID	Lethbridge (RF Sink 65)	0.18
RID 391	SMRID	Lethbridge (RF Sink 65)	0.18
SMRID 380	SMRID	Lethbridge (RF Sink 65)	0.18
SMRID 381& 382	SMRID	Irrigation District Retention Pond (RF Sink 7)	0.18
TID 392	SMRID	Oldman-Little Bow Confluence (RF Sink 66)	0.18
TID 393 & 394	SMRID	Oldman-Bow Confluence (RF Sink 67)	0.18
SMRID 383 & 384	SMRID	Oldman-Bow Confluence (RF Sink 67)	0.18
SMRID 385 & 386	SMRID	Medicine Hat (RF Sink 7)	0.18
SMRID 387, 388 & 389	SMRID	Medicine Hat (RF Sink 6)	0.18

E.7 Hydropower Plant Properties

Table E.9 Hydropower plant properties of the STRIBS system

Plant Name	First on Stream	Capacity (MW)	Gross Head (m)	Head Loss (m)	Turbine Efficiency	Generator Efficiency	Owner
Belly River Plant	1991	3	N/A	0.9	0.95	0.95	TAC
Waterton Plant	1992	3	N/A	0.9	0.95	0.95	TAC
St. Mary Plant	1992	2	N/A	0.9	0.95	0.95	TAC
Taylor Chute	2000	13	N/A	0.9	0.95	0.95	TAC
Raymond Plant	1994	18.5	44	0.9	0.95	0.95	IP
Irricana Plant (Drop 4, 5 and 6 Hydroelectric Plant)	2004	7	15.2	0.9	0.95	0.95	IP
Chin Chute Plant	1994	11	40.5	0.9	0.95	0.95	Irrican Power

Note:

- There are seven Run-of-the-river (RR) hydropower plants in the STRIBS system and together can produce a maximum of 57.5 MW of electricity
- The hydropower plant information was collected from Alberta Energy’s online resources (Alberta Utilities Commission, 2010). The head loss, turbine, and generator efficiency data were not available, and this study assumed a reasonable value for model development

E.8 System Priority

The MODSIM Decision Support System allocates water based on the priority of water resources components assigned by the user. The present study used a manual calibration approach to obtain priority rankings of the system and presented below in Table E.10.

Table E.10 Priority of water resource system components considered for the STRIBS model development

MODSIM ID	Priority	Node Type
MW_807_USApport	1	US-Canada Apportionment
FT_172	5	MSR
FT_184	5	MSR
All major withdrawal nodes	20	Non-Irrigation Demand
FT_476	30	MSR
All irrigation district nodes	30	Irrigation Demand
All private irrigation nodes	40	Irrigation Demand
R_278	60	Reservoir
R_277	60	Reservoir
R_276	60	Reservoir
R_275	60	Reservoir
R_274	60	Reservoir
R_273	60	Reservoir
R_272	60	Reservoir
R_271	60	Reservoir
R_270	60	Reservoir
R_209	60	Reservoir
R_210	60	Reservoir
R_207	60	Reservoir
FT_182	70	MSR
FT_181	70	MSR
FT_180	70	MSR
FT_191	70	MSR
R_208	4999	Reservoir
R_206	4999	Reservoir

E.9 Model Validation and Results

To validate the developed STRIBS model's credibility and simulation results, this study considered following validation approaches:

- ➢ Check the water balance of the developed model,
- ➢ Comparison of simulated streamflow and reservoir elevation with available recorded data as well as results of the existing water management model (e.g., WRMM) at the outlet of the STRIBS system, e.g., Belly River flow at the mouth and St. Mary River flow near Lethbridge.

Table E.11 Water balance of the developed STRIBS model

Category	STRIBS
Inflow from rivers (MCM)	37.472
Outflow to downstream (MCM)	17.187
Allocation to demand (MCM)	22.208
Reservoir storage gain (+) / loss (-) (MCM)	-0.026311
Reservoir evaporation (MCM)	1.184
Reservoir precipitation (MCM)	0.324
Return flow (MCM)	2.758
Total available water (MCM)	40.553
Total outflow (MCM)	40.553
Difference (MCM)	0.000
Error (%)	0.0010%

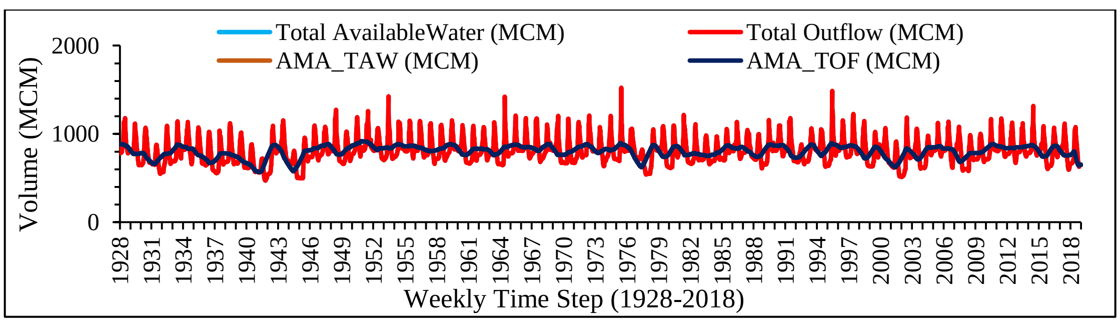
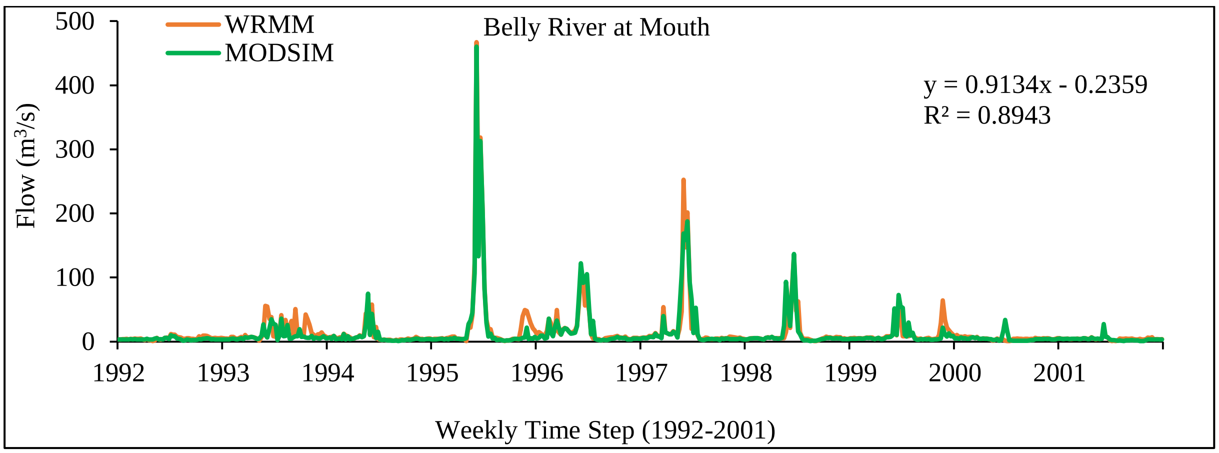


Figure E.8 Water balance of the STRIBS system after MODSIM simulation for each time step and their Annual Moving Average (AMA) of total available water (TAW) and total outflow (TOF)

Table E.12 Average streamflow of the Belly and St. Mary rivers at the outlet of the STRIBS system

Belly River at Mouth			
DSS	Minimum	Maximum	Average
WRMM (m^3/s)	0.93	467.27	13.87
MODSIM (m^3/s)	0.93	460.32	12.73
St. Mary River near Lethbridge			
WRMM (m^3/s)	2.75	136.41	10.29
MODSIM (m^3/s)	2.75	251.07	13.22
Observed (m^3/s)	1.60	271.93	12.94



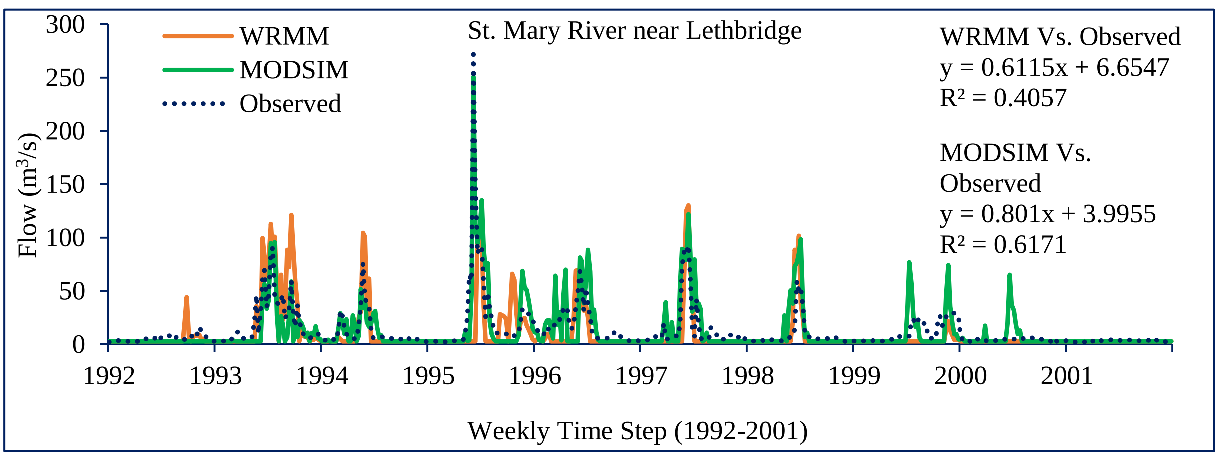


Figure E.9 Outflow from the STRIBS system through the Belly River (top) and St. Mary River (bottom)

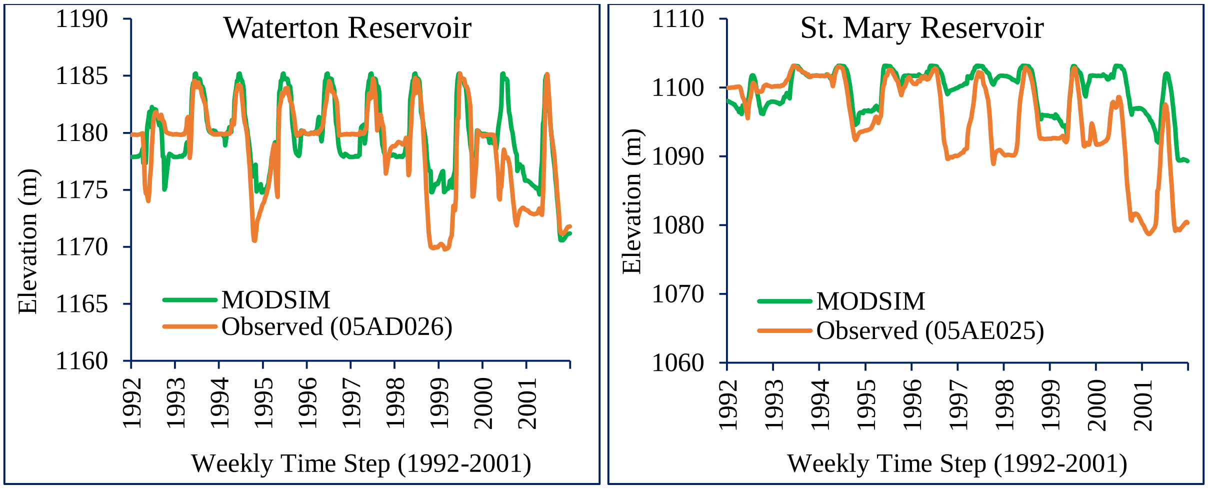


Figure E.10 Modsim simulation results for the Waterton and St. Mary reservoirs

E.10 References

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Appendix F: North Saskatchewan River Basin-Alberta (NSR-AB)

F.1 North Saskatchewan River Basin in Alberta: System Diagram

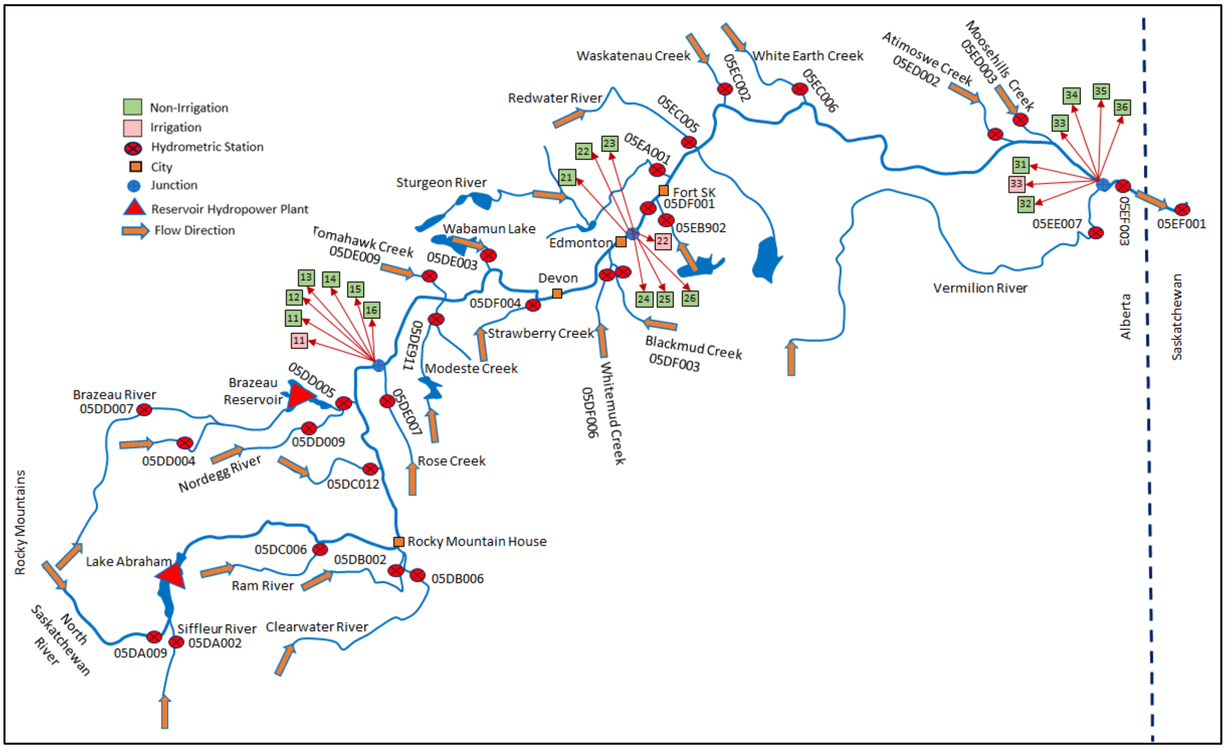

Figure F.1 Schematic of the water resources system of the North Saskatchewan River Basin in Alberta (NSR-AB) from the Rocky Mountains to the Alberta-Saskatchewan border

Note:

- River network in the North Saskatchewan River Basin Alberta (NSR-AB) was obtained from the HYDAT Database (WSC, 2019), and reports of the North Saskatchewan Watershed Alliance (NSWA, 2008)

F.2 Reservoir Properties

F.2.1 General Properties

Table F.1 General properties of reservoirs in the NSR-AB

Reservoir Name	Bighorn	Brazeau
First on Stream	1972	1961
Dead Storage Level (DSL) (m)	1283.06	945.56
Full Supply Level (FSL) (m)	1321.36	966.26
Storage Capacity (MCM)	1410.04	486.30
Latitude	52.216909	52.962548
Longitude	-116.439575	-115.593731

Note:

- Recorded daily reservoir elevation was obtained from the HYDAT database and then estimated the weekly average
- Historical weekly minimum and maximum elevation were considered as dead storage level (DSL) and full supply level (FSL), respectively. The storage difference between DSL and FSL was considered as the storage capacity of the reservoir
- MCM= Million Cubic Meter
- Reservoir latitude and longitude were obtained from the Google Earth map

F.2.2 Reservoir Area-Capacity-Elevation (ACE)

Table F.2 Area (in square kilometer), Capacity (in cubic decameter) and Elevation (in meter) of the reservoirs considered in NSR-AB model development

Bighorn Reservoir (Station ID# 05DC009)					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.00	0.00	1283.06	29.90	703750.00	1306.60
23.61	187500.00	1291.00	30.08	720127.68	1307.00
22.85	250000.00	1294.00	30.26	735943.96	1307.38
25.10	375000.00	1298.00	30.07	750000.00	1308.00
26.56	450000.00	1300.00	31.32	875000.00	1311.00
27.11	500000.00	1301.50	32.32	1000000.00	1314.00
28.29	550000.00	1302.50	33.66	1075000.00	1315.00
29.63	650000.00	1305.00	34.30	1250000.00	1319.50
29.83	697884.16	1306.46	36.82	1410038.41	1321.36

Brazeau Reservoir (Station ID# 05DD006)					
Area	Capacity	Elevation	Area	Capacity	Elevation
0.00	0.00	945.56	17.34	230843.43	958.87
5.81	20000.00	949.00	17.41	233532.33	958.97
9.01	40000.00	950.00	17.44	234535.92	959.01
8.75	52000.00	951.50	17.73	245000.65	959.38
12.25	85000.00	952.50	19.43	300000.00	961.00
11.85	100000.00	954.00	21.69	400000.00	964.00
16.08	200000.00	958.00	23.49	486302.49	966.26

Note:

- ➢ Reservoir capacity and elevation data were obtained from the online portal of the Alberta Environment (Alberta Environment, 2018a)
- ➢ The reservoir surface area was obtained manually from the Google Earth map, and based on the proportion of volume, the area was estimated for different elevations

F.2.3 Reservoir Operating Policy

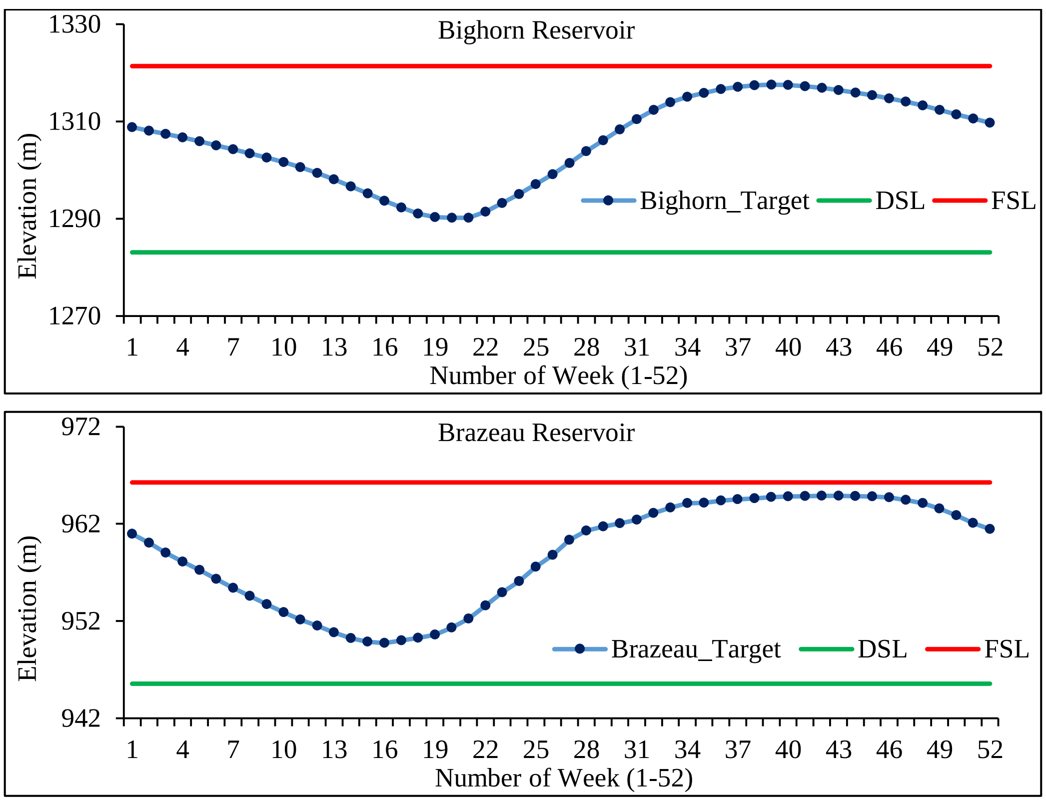

Figure F 2 Reservoir operating policy considered in the NSR-AB model development

Note:

The reservoir operation policy was not available for public access or research purpose. The operating policy (target level) was deduced based on 1992-2001 recorded weekly average elevation of reservoirs. All reservoir elevation data were obtained from the HYDAT database (WSC, 2019), and the online portal of Alberta Environment (Alberta Environment, 2018a).

F.2.4 Reservoir Evaporation and Precipitation

Table F.3 Evaporation, precipitation and weighting factor for the NSR-AB reservoirs

Reservoir	Evaporation Station	Weighting Factor	Precipitation Station	Weighting Factor
Bighorn	Calgary	0.97	Calgary	1.37
Brazeau	Calgary	0.94	Calgary	1.49

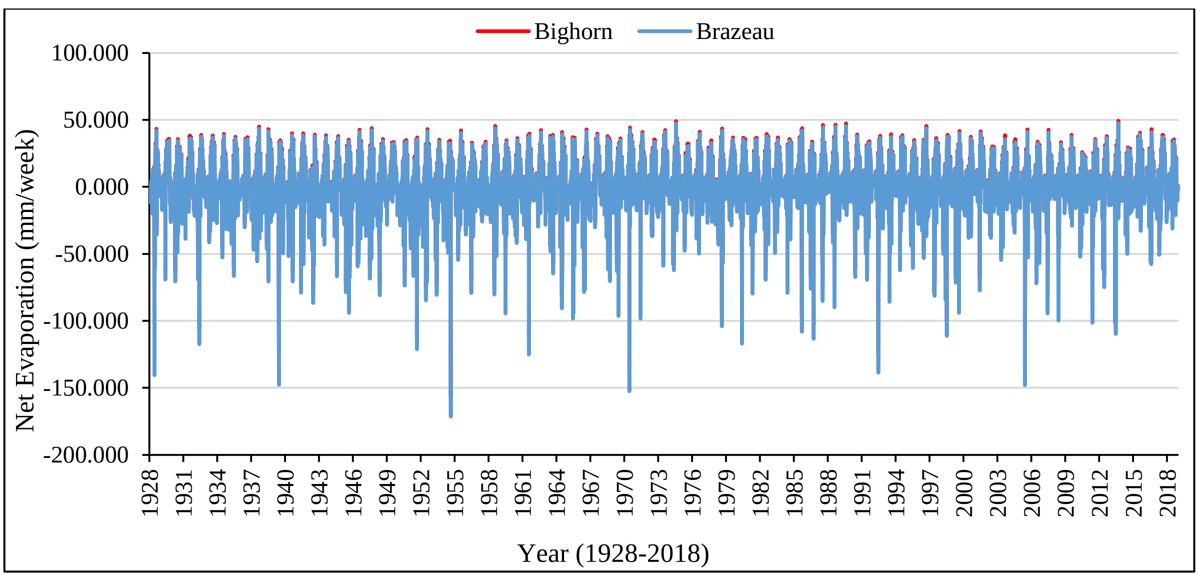

Figure F.3 Net evaporation of the NSR-AB reservoirs

Note:

- Reservoir evaporation and precipitation data at Calgary station were obtained from the WRMM of the South Saskatchewan River, Alberta (1928-2001), and online portal of Alberta Agriculture and Forestry (2002-2018) (Government of Alberta, 2019b)

➢ A weighting factor was used in the adjustment process, which can be defined as the ratio of annual precipitation and evaporation in NSR-AB reservoir sites to those of collected data at Calgary station

F.3 Inflow Properties

Table F.4 List of natural streamflow considered in the NSR-AB model development

Sl.	MODSIM Inflow Name	Inflow Type	Inflow ID	MAI (MCM)
1	In_Siffleur_05DA002	Main	05DA002	352.46
2	In_RamMouth_05DC006	Main	05DC006	682.20
3	In_PrarieCr_05DB002	Main	05DB002	200.82
4	In_ClearwaterWat_05DB006	Main	05DB006	815.41
5	In_NSR_WHIRLP_05DA009_Nat	Main	05DA009	2482.58
6	In_Baptiste_05DC012	Main	05DC012	287.37
7	In_Blackmud_05DF003	Main	05DF003	17.43
8	In_Brazeau_05DD007	Main	05DD007	1352.97
9	In_BrownCr_05DD004	Main	05DD004	60.38
10	In_Nordegg_05DD009	Main	05DD009	219.47
11	In_RoseCr_05DE007	Main	05DE007	88.46
12	In_Strawberry_05DF004	Main	05DF004	56.30
13	In_Tomahawk_05DE009	Main	05DE009	12.56
14	In_Wabakum_05DE003	Main	05DE003	13.04
15	In_Whitemud_05DF006	Main	05DF006	13.04
16	In_PointeCr_05EB902	Main	05EB902	5.90
17	In_Sturgeon_05EA001	Main	05EA001	160.22
18	In_RedWat_05EC005	Main	05EC005	24.54
19	In_WaskatenauCr_05EC002	Main	05EC002	3.29
20	In_WhiteEr_05EC006	Main	05EC006	23.32
21	In_Atimoswe_05ED002	Main	05ED002	5.29
22	In_Moosehills_05ED003	Main	05ED003	1.45
23	In_Vermilion_05EE007	Main	05EE007	46.03

Note:

- The natural flow of the North Saskatchewan River was considered at the Alberta-Saskatchewan border from 1928 through 2018
- The first water management structure at the NSR upstream was constructed in 1962 (Table F.1). Therefore, before 1962 (1928-1961), the NSR flow was natural, which was obtained from the HYDAT database (WSC, 2019). However, natural flow from 1962-2018 was estimated by satisfying all demands and keeping reservoirs at the historical level. The natural flow then distributed to all inflows (Table F.4) based on their proportion
- MAI= Mean Annual Inflow
- MCM= Million Cubic Meter

F.4 Channel Properties

Table F.5 Minimum streamflow requirements and maximum channel capacity of the North Saskatchewan River

Natural Channel	Minimum (m^3/s)	Maximum (m^3/s)	Note
NSR up to AB-SK border	0	5000	Assumed based on SSR properties
NSR at AB-SK border	FT_NSR05EF001_DeerCr	5000	05EF001

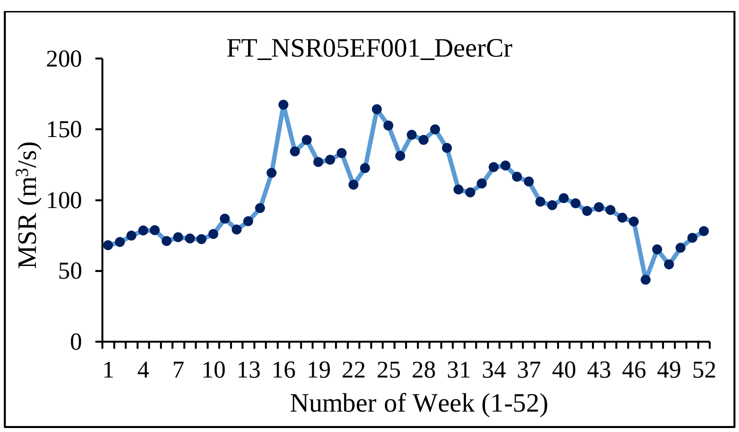

Figure F.4 Minimum streamflow requirements (MSR) of the North Saskatchewan River in Alberta

Note:

- The maximum flow capacity of the North Saskatchewan River was considered as same as the South Saskatchewan River
- Historical weekly minimum flow (controlled flow after reservoir construction) at the Alberta-Saskatchewan border was considered as minimum streamflow requirements for the North Saskatchewan River at downstream

F.5 Demand Properties

Table F.6 Licensed water demand, actual water use, and return flow fraction considered in the NSR-AB model

Demand Type	Licensed Demand (Dam3)	Actual Use (%)	Return Flow Fraction	MODSIM ID
Municipal and Residential	43382.00	22	0.03	MW_11, MW_21, MW_31
Agriculture (Livestock)	5983.50	90	0.00	MW_12, MW_22, MW_32
Agriculture (Irrigation)	9555.90	100	0.01	Irr_11, Irr_22, Irr_33
Commercial	11083.70	100	0.10	MW_13, MW_23, MW_33
Petroleum	77567.50	38	0.10	MW_14, MW_24, MW_34
Industrial	206979.70	44	0.85	MW_15, MW_25, MW_35
Other	25899.30	100	0.10	MW_16, MW_26, MW_36

Note:

- Annual irrigation and non-irrigation demand (licensed and actual demand) data and return flow fraction at NSR-AB area were obtained from the Alberta Environment water demand study (Alberta Environment, 2008a)

- Annual actual non-irrigation demand was equally distributed over 52 weeks of the year. Annual actual irrigation demand was equally distributed over the irrigation season (April to October; week# 14 to 44)
- All demands (irrigation and non-irrigation) were divided into three portions and placed them at three different points of the system, e.g., upstream of Edmonton, at Edmonton and downstream of Edmonton, based on an approximation focusing on the spatial water demand distribution map of the NSR-AB (Alberta Environment, 2008a)

F.6 Hydropower Properties

Table F.7 Properties of the hydropower plants considered in the NSR-AB model

Plant Name	First on stream	Capacity (MW)	Storage Reservoir	Gross Head (m)	Head Loss (m)	Turbine Efficiency	Generator Efficiency
Bighorn Plant	1972	120	Bighorn	95	0.9	0.95	0.95
Brazeau Plant	1965	355	Brazeau	126	0.9	0.95	0.95

Note:

- The hydropower plant information, e.g., date of impoundment and capacity, was obtained from the online portal of the TransAlta Corporation. The gross head data of the hydropower plant was collected from Alberta Energy’s online resources (Alberta Utilities Commission, 2010). The head loss, turbine, and generator efficiency data were not available, and this study assumed a reasonable value for model development.

F.7 System Priority

Table F.8 NSR-AB system components and their respective priority considered in MODSIM simulation

MODSIM Node Name	Node Type	MODSIM Priority
All Major Withdrawal (MW) Nodes	Non-Irrigation	40
All Irrigation (Irr) Nodes	Irrigation	50
R2_Brazeau	Reservoir	60
FT_NSR05EF001_DeerCr	MSR	70
R1_BigHorn	Reservoir	100

Note: The water allocation priority of different water resources components of the system was deduced based on the manual calibration with an objective to satisfy reservoir target elevation and keep streamflow close to observed gauge data.

F.8 NSR-AB Schematic in MODSIM Graphical User Interface (GUI)

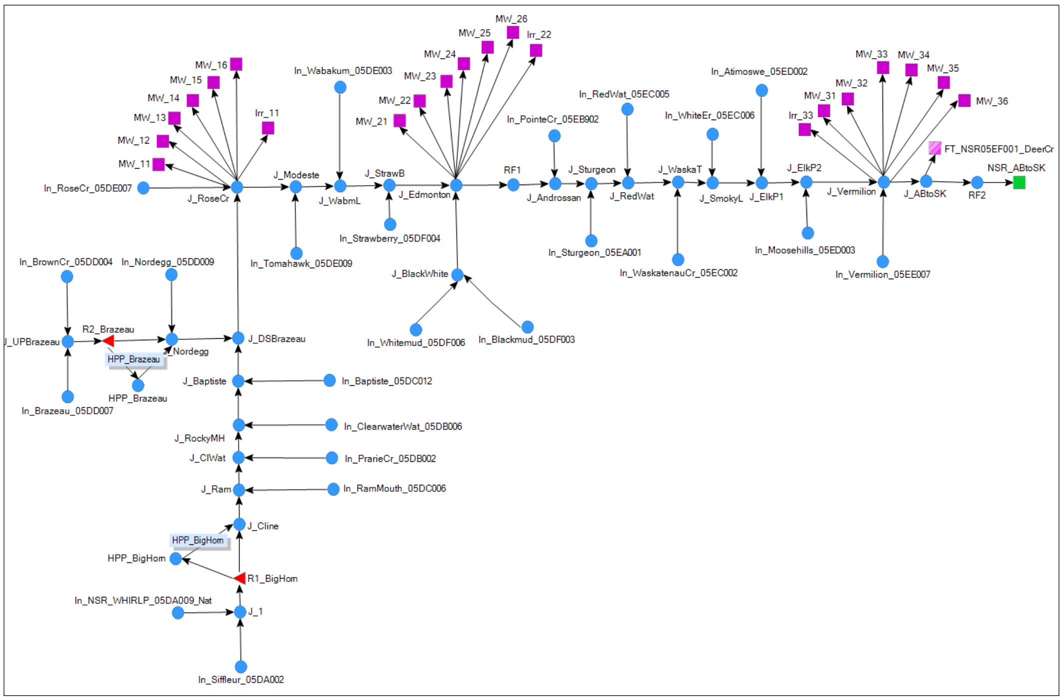

Figure F.5 Developed NSR-AB model schematic in MODSIM GUI

F.9 Model Validation and Results

Table F.9 Mean annual water balance of the developed NSR-AB model

Category	NSR-AB
Inflow from rivers (MCM)	132.799
Outflow to downstream (MCM)	128.619
Allocation to demand (MCM)	5.125
Reservoir storage gain (+) / loss (-) (MCM)	0.006
Reservoir evaporation (MCM)	0.385
Reservoir precipitation (MCM)	0.236
Return flow (MCM)	1.100
Total available water (MCM)	134.141
Total outflow (MCM)	134.129
Difference (MCM)	0.012
Error (%)	0.009%

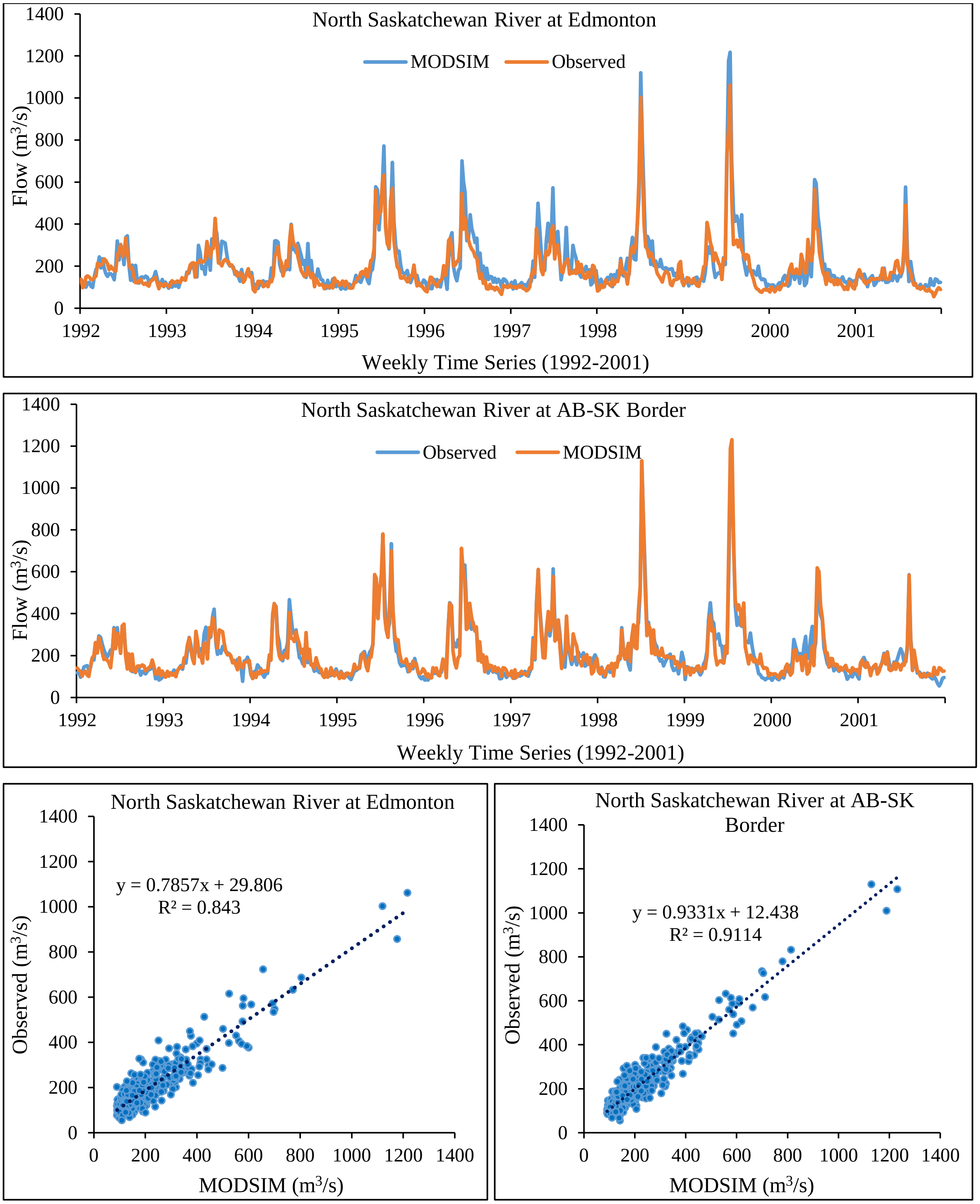

Figure F.6 Comparison between MODSIM simulated and observed streamflow for the North Saskatchewan River at Edmonton and Alberta (AB)-Saskatchewan (SK) border

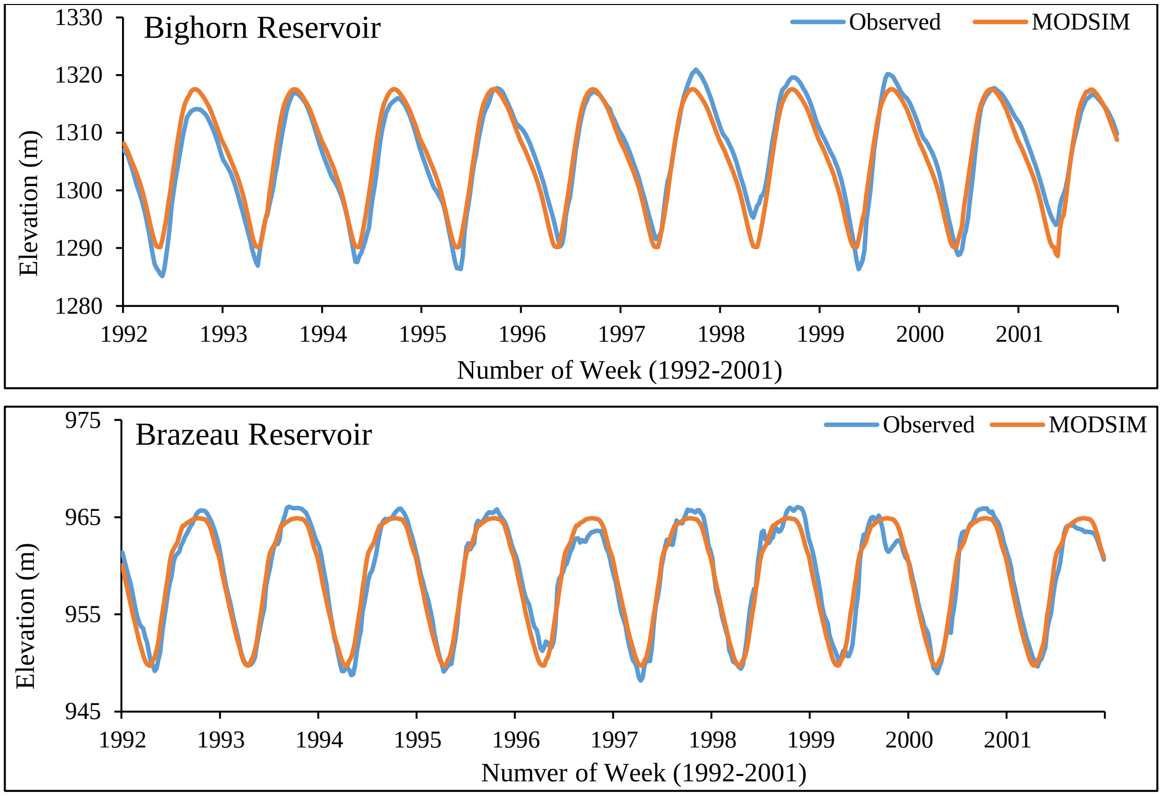

Figure F.7 MODSIM simulated elevation for the NSR-AB reservoirs

F.10 References

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Appendix G: North Saskatchewan River Basin-Saskatchewan (NSR-SK)

G.1 North Saskatchewan River Basin-Saskatchewan: System Diagram

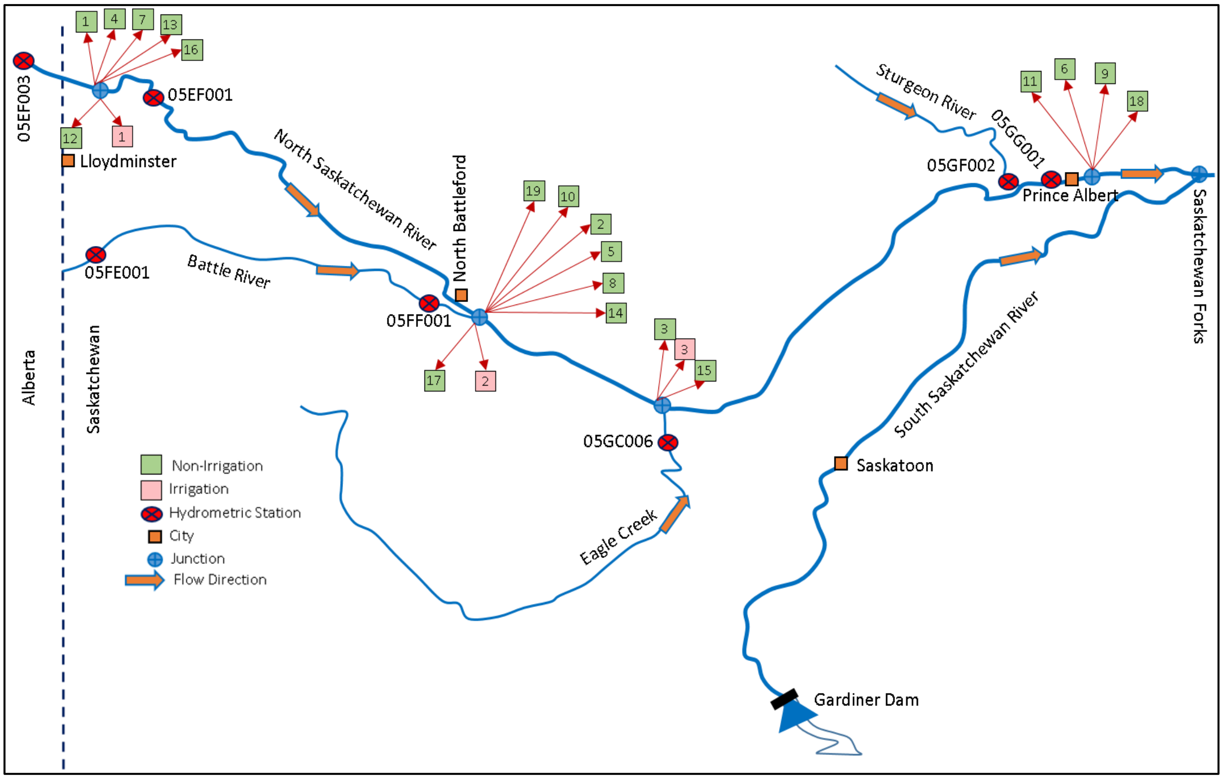

Figure G.1 Schematic of the North Saskatchewan River (NSR) basin water resources system in Saskatchewan, from the Alberta-Saskatchewan border to Prince Albert, Saskatchewan

Note:

River network in the North Saskatchewan River (NSR) Basin in Saskatchewan (NSR-SK) was obtained from the HYDAT Database (WSC, 2019).

G.2 Inflow Properties

Table G.1 Streamflow information considered in the NSR-SK model development

Sl.	MODSIM Inflow Name	Inflow Type	Inflow ID	MAI (MCM)
1	In_BattleMouth_05FF001	Main	05FF001	952.13
2	In_Sturgeon_05GF002	Main	05GF002	218.46
3	In_EagleCr_05GC006	Main	05GC006	51.51
4	In_NSR_ABtoSK_05EF001	Main	05EF001	6706.58

Note:

- The NSR flow from Alberta (AB) to Saskatchewan (SK) (In_NSR_ABtoSK_05EF001) was taken from the developed NSR-AB model
- The natural flow of the NSR at Prince Albert, SK, was obtained from the WRMM model of SK (1928-1986) and then extended until 2018. The data was extended based on the relationship between the NSR natural flow at the AB-SK border (which was estimated during the NSR-AB model development) and at Prince Albert, SK
- The incremental natural flow of the NSR from the AB-SK border to Prince Albert, SK, was distributed to other inflows (Table G.1) based on their respective flow proportion

G.3 Channel Properties

Table G.2 Minimum streamflow requirements (MSR) and the maximum capacity of the North Saskatchewan River in Saskatchewan

Natural Channel	Minimum (m^3/s)	Maximum (m^3/s)
NSR (AB-SK Border to Prince Albert)	0	5000
NSR at Prince Albert	32.5	5000

Note:

- The maximum flow capacity of the NSR was considered as same as the South Saskatchewan River (SSR), obtained from the WRMM SK model
- The minimum streamflow requirements of the NSR at Prince Alberta were obtained from the literature (Kulshreshtha, Bogdan, *et al.*, 2012)

G.4 Demand Properties

Table G.3 Annual water demand in the NSR-SK area

Demand Category	Actual Demand (Dam^3)	MODSIM ID	Return Flow Fraction
Agriculture (Irrigation)	37377.00	Irr_1, Irr_2, Irr_3	0.15
Agriculture (Livestock and other)	4034.00	MW_1, MW_2, MW_3	0.15
Industrial (Manufacturing)	3062.00	MW_4, MW_5, MW_6,	0.78
Industrial (Salt manufacture & Power Generation)	2399.00	MW_7, MW_8, MW_9	0.00
Municipal (North Battleford)	882.09	MW_10	0.48
Municipal (Prince Albert)	2834.15	MW_11	0.48
Municipal (Lloydminster)	1786.84	MW_12	0.48
Domestic (Small towns)	2163.41	MW_13, MW_14, MW_15	0.48
Domestic (Rural) First Nations' Water Demand Other Institutional Water Demand	3220.89	MW_16, MW_17, MW_18	0.48
Commercial (Resorts)	89.70	MW_19	0.05

Note:

- Annual actual surface water demand (irrigation and non-irrigation) was obtained from the NSR demand study published by the Water Security Agency of Saskatchewan (Kulshreshtha *et al.*, 2012)
- Annual non-irrigation demand was equally distributed over 52 weeks the year
- Annual irrigation demand was equally distributed over the irrigation season (April to October; week# 14 to 44)
- Both irrigation and non-irrigation demand locations were approximated in Figure G.1based on the water demand study report (Kulshreshtha *et al.*, 2012)

G.5 System Priority

Table G.4 Priority of water resources components used to develop the NSR-SK model

MODSIM Node Name	Node Type	MODSIM Priority
MW_11	Non-Irrigation Demand	20
MW_10	Non-Irrigation Demand	20
MW_12	Non-Irrigation Demand	20
MW_18	Non-Irrigation Demand	30
MW_13	Non-Irrigation Demand	30
MW_14	Non-Irrigation Demand	30
MW_17	Non-Irrigation Demand	30
MW_16	Non-Irrigation Demand	30
MW_15	Non-Irrigation Demand	30
MW_4	Non-Irrigation Demand	40
MW_6	Non-Irrigation Demand	40
MW_5	Non-Irrigation Demand	40
MW_3	Non-Irrigation Demand	50
MW_7	Non-Irrigation Demand	50
MW_8	Non-Irrigation Demand	50
MW_2	Non-Irrigation Demand	50
MW_9	Non-Irrigation Demand	50
MW_1	Non-Irrigation Demand	50
Irr_3	Irrigation Demand	60
Irr_2	Irrigation Demand	60
Irr_1	Irrigation Demand	60
MW_19	Non-Irrigation Demand	70
FT_NSR_MinFlow	MSR at Prince Albert	100

Note: Priority for different water resources components of the NSR-SK system, e.g., demand and MSR, were deduced based on the manual calibration with an objective to satisfy all demands and keep streamflow close to observed gauge data at Prince Albert, SK.

G.6 NSR-AB Schematic in MODSIM Graphical User Interface (GUI)

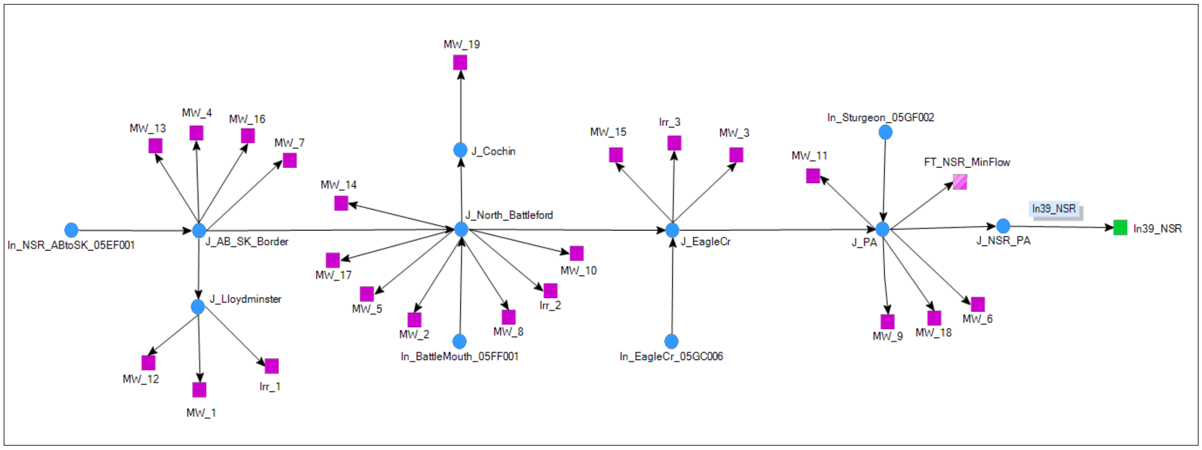

Figure G.2 Developed NSR-SK model in MODSIM GUI

G.7 Model Validation and Results

Table G.5 Mean annual water balance of the developed NSR-SK model

Category	NSRA-SK
Inflow from rivers (MCM)	152.057
Outflow to downstream (MCM)	151.205
Allocation to demand (MCM)	1.112
Reservoir storage gain (+) / loss (-) (MCM)	0.000000
Reservoir evaporation (MCM)	0.000
Reservoir precipitation (MCM)	0.000
Return flow (MCM)	0.261
Total available water (MCM)	152.318
Total outflow (MCM)	152.318
Difference (MCM)	0.000
Error (%)	0.0000%

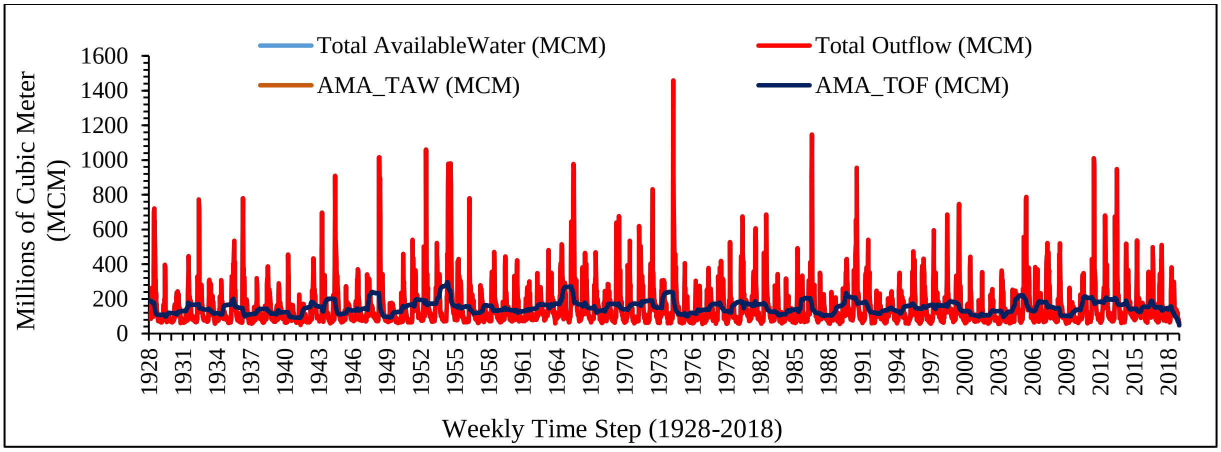

Figure G.3 Water balance of the developed NSR-SK model at each time step (weekly), and annual moving average (AMA) of total available water (TAW) and total outflow (TOF)

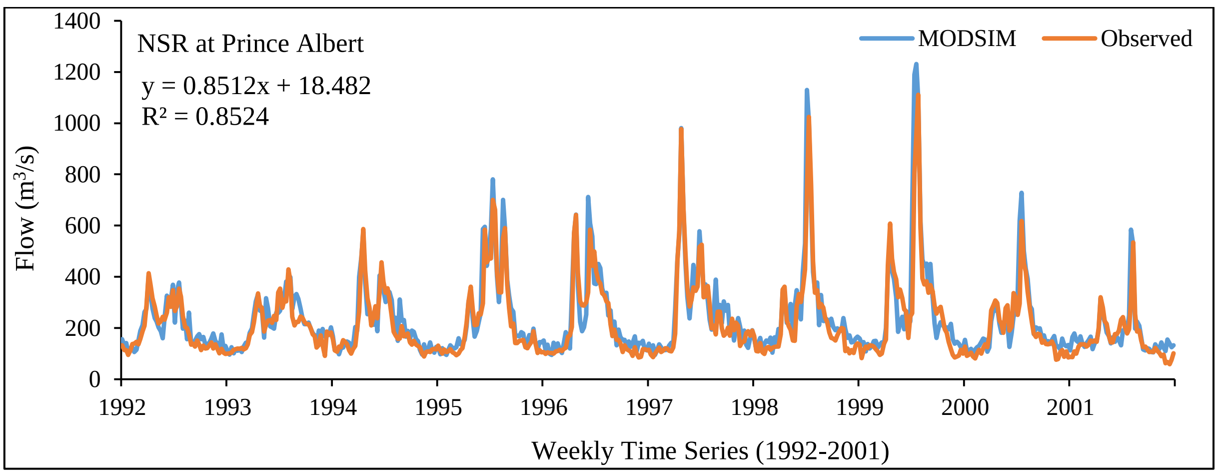

Figure G.4 MODSIM simulated streamflow for the NSR at Prince Albert, Saskatchewan

G.8 References

Kulshreshtha, Suren, Ana Bogdan, and Cecil Nagy. 2012. *Present and Future Water Demand in the North Saskatchewan River Basin*.

Water Survey of Canada (WSC). 2019. “National Water Data Archive: HYDAT.”

Appendix H: Supplementary Materials for the Integrated Water Management Model Development

Description: This section of the appendix presents the considerations which were made to integrate developed sub-models for the SaskRB.

H.1 Integration Process of the Sub-models

The present study used the MODSIM customization option to integrate all seven sub-models into one platform that can simulate water allocation from the Canadian Rocky Mountains to the Saskatchewan River Delta. The integration process was accomplished in such a way that individual sub-model can preserve local operating policy and properties and provide the outputs which were then used as inputs to the downstream sub-models. The programming language C# was used to develop the code for this automatic integration process utilizing the MODSIM customization option. The sub-models were run based on their sequence from upstream to downstream of the SaskRB (Figure H.1). The sub-models connectivity in the integration process is presented below in Table H.1.

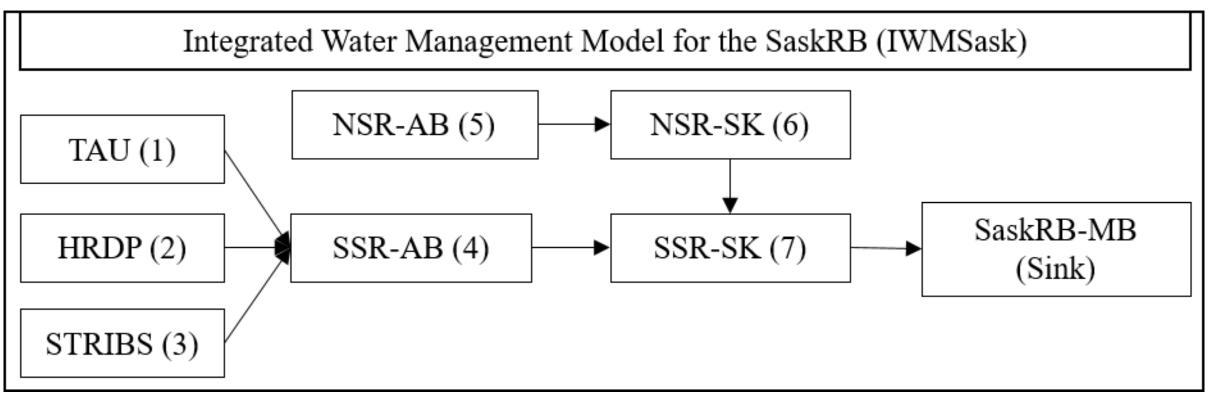

Figure H. 1 Sequence of sub-model simulation to develop the integrated water management model for the SaskRB (IWMSask)

Table H.1 The integration process of various sub-models to develop one integrated water management model for the SaskRB

Upstream Sub-model	Output Link from Upstream Sub-model	Input Node to Downstream Sub-model	Downstream Sub-model
TAU	Ghost Dam Release	In284_TAU_GHOSTRel	SSR-AB
TAU	Flow below Bearspaw Dam- Ghost Dam Release	In285_TAU_BPAWLOCL	SSR-AB
STRIBS	Outflow from Belly River	In17_STRIBS_Belly	SSR-AB
STRIBS	Outflow from St. Mary River	In208_STRIBS_StMary	SSR-AB
STRIBS	SMRID Return flow 1	In15_STRIBS_RT1	SSR-AB
STRIBS	SMRID Return flow 2	In13_STRIBS_RT2	SSR-AB
STRIBS	SMRID Return flow 3	In14_STRIBS_RT3	SSR-AB
STRIBS	SMRID Return flow 4	In16_STRIBS_RT4	SSR-AB
HRDP	Outflow from Highwood River at Mouth	In289_HWR_Mouth	SSR-AB
HRDP	Outflow from Little Bow River at Traverse Reservoir	In230_LBOW_Travrs	SSR-AB
SSR-AB	Outflow from SSR at AB-SK Border	In30_SSR	SSR-SK
NSR-AB	Outflow from NSR at AB-SK Border	In_NSR_ABtoSK_05EF001	NSR-SK
NSR-SK	NSR at Prince Albert	In39_NSR	SSR-SK