INTEGRATED MANAGEMENT OF WATER RESOURCE SYSTEMS UNDER CHANGING WATER AVAILABILITY, POLICY, AND IRRIGATION EXPANSION PLANS

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Abstract

Conventional water resource management has been based on the assumption of stationarity in the characteristics of the water resource systems. However, the validity of this assumption is questionable due to changing climate and increasing human activities. The current level of uncertainty inherent in the projection of future natural and anthropogenic conditions has also complicated water resource planning and management. As a result, there is a fundamental need to acknowledge the uncertainty associated with water resource systems and propose improved management schemes under uncertainty.

This thesis presents three developments to assist in understanding system behavior under historical and changing conditions, and to propose an alternative framework for decision making under uncertain conditions. The three parts are put together and applied to the Saskatchewan River Basin (SaskRB) in Saskatchewan, which is a strategically important water resource system in western Canada. In brief, first a Sustainability-oriented Water allocation, Management, and Planning ($SWAMP_{SK}$) model is developed using the System Dynamics approach. This water resource model captures the causal relationships among system components and combines various aspects of the water resource system, such as water allocation, irrigation demand, and economic evaluation within an integrated system. Second, $SWAMP_{SK}$ is used to map the vulnerability and sectorial trade-offs in the SaskRB in Saskatchewan under changing water availability and irrigation expansion. Using a bottom-up approach, a wide range of streamflow conditions is stochastically generated to accommodate likely scenarios of change in water availability. The streamflow ensemble and alternative irrigation expansion scenarios are used in

$SWAMP_{SK}$ for evaluating the water resource system's performance under potential changes in natural conditions and irrigated areas. Third, an innovative probabilistic framework is proposed to evaluate the risk in system behavior under changing conditions and to identify the contributions of various changing conditions on the overall system performance. For this purpose, the empirical probability distributions of system performance are used to quantify the individual and joint impacts of changing conditions on the system performance with the goal of proposing policies that minimize the risk of undesired changes in system.

This thesis provides a set of new and strategically-important insights to the water resource system in Saskatchewan. In brief, increase in irrigation area can raise the total economic benefit except in extremely dry flow conditions, but with some cost of decreasing water availability in downstream regions. Saskatchewan can meet the inter-provincial commitment under changes in flow regime and irrigation expansion. Results also show that no one specific policy can provide the optimal option for water resource management under all changing flow and irrigation expansion conditions and the joint impacts of changing water availability, policy, and irrigation expansion are complex nonlinear functions of individual drivers. This thesis also offers a set of new modeling tools that can be used to assist decision making under uncertainty. In particular, the proposed risk-based framework allows an explicit understanding of the variations in the system performance as a result of changing natural and/or anthropogenic conditions and can be transferred to decision making applications.

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List of Abbreviations

AB	Alberta
AET	Actual evapotranspiration
AFH	Annual flow hydrograph
BAU	Business-as-usual
CLD	Causal-loop-diagram
CV	Coefficient of variation
ECDF	Empirical cumulative distribution function
ED	Empirical distribution
EPDF	Empirical probability distribution function
ET	Evapotranspiration
GCM	Global Climate Model
HL	Head loss
HM	Hydropower maximization
ID	Irrigation demand
IDM	Irrigation demand model
IE	Irrigation expansion
IWRM	Integrated water resource model
LD	Lake Diefenbaker
MARE	Mean absolute relative error
MCM	Million cubic meter
MW	Megawatt

NB	Net benefit
NPV	Net present value
NSR	North Saskatchewan River
PC	Policy change
PNB	Provincial net benefit
RMSE	Root mean square error
SaskRB	Saskatchewan River Basin
SCS	Soil Conservation Service
SD	System Dynamics
SIPA	Saskatchewan Irrigation Projects Association
SK	Saskatchewan
SM	Soil moisture
SR	Saskatchewan River
SRD	Saskatchewan River Delta
SS	Supply Security
SSR	South Saskatchewan River
SWAMP	Sustainably-oriented water allocation, management, and planning
TL	Tobin Lake
SWSA	Saskatchewan Water Security Agency
WAC	Water availability change
WP	Wilting point
WRMM	Water resources management model

Chapter 1 - Introduction

1.1 Background and problem definition

Traditional water resource management is often based on the assumption that key components of water resource systems i.e., water availability and water demand have time-invariant statistical properties. This "stationarity assumption", however, has become questionable over the past few decades due to the changes observed as a result of warming climate and increasing human activities (Milly et al., 2008). On one hand, climate change has already altered key meteorological characteristics, such as regional and global temperature, and has consequently intensified the hydrological cycle across these spatial scales (Groisman et al., 2001; Nijssen et al., 2001; Oki and Kanae, 2006). This has resulted in significant changes in natural streamflow regime in various parts of the globe (Milly et al., 2005; Barnett et al., 2005; Viviroli et al., 2010). On the other hand, increasing water demands and withdrawal as well as land-use change have also contributed to altering streamflow conditions (Magilligana and Nislow, 2005; Nazemi and Wheater, 2015a, b) and have increased the complexity of water resource management across various scales (Wheater and Gober, 2015).

Relying on historical data and system characteristics, therefore, cannot serve the needs for water resource management under changing conditions (Varis et al., 2004; Pahl-Wostl, 2007; Dessai et al., 2009; Beven, 2011). New insights into the possible future state of water availability, water demand, and water resource management are required. This is, however, extremely challenging. For instance, understanding the future states of water availability requires the capability of projecting both climate and hydrological processes. At the current state of knowledge, this is considered to be a limiting factor (Karl and Trenberth, 2003; Fowler et al., 2007). The results obtained from Global Climate Models (GCMs), which are the most advanced scientific tools available for representing the climate processes (Field, 2014), are highly uncertain due to considerable limitations in accounting for underlying physical processes and significant differences across various models (Maurer and Duffy, 2005; Beniston et al., 2007; Wilby, 2010; Zhang et al., 2011). Even without these uncertainties, the results of GCMs are not at the scale required for water resource management at regional and catchment scales (Buytaert et al., 2010; Kundzewicz and Stakhiv, 2010). In addition, hydrological models, which are required to translate the climate projections into future estimate of water availability, include a great deal of uncertainty due to the underlying assumptions, process simplifications, and the lack of identifiable parameterizations (Jin et al., 2010). In addition, projections of future water demands are challenging, due to uncertainties in future population growth, water policies, technological innovation, water price, and socio-economic variables (World Water Assessment Programme, 2009). At this stage, when projections of both water demand and water availability are largely uncertain understanding the future of water resource management, which links the water demand to water availability, becomes also uncertain. This creates an extremely complex condition for the assessment of water resource systems under future conditions, known as the "deep uncertainty" (Bates, 2008; Hallegatte et al., 2012; Gober, 2014).

1.2 Purpose and research objectives

The deep uncertainty in assessment of water resource systems under changing conditions should be recognized and reduced. So far, various approaches have been suggested to improve water resource management under uncertainty, which will be discussed in detail in Section 1.4. In brief, these methodologies emphasize the need for more holistic system models that can assist in understanding the system behavior under changing conditions and can capture causal relationships among various aspects of the system under investigation (Vucetic and Simonovic, 2011). In addition, it is suggested that instead of focusing on projecting the future elements of water resource management, it is more logical to evaluate the sensitivity of the system to multiple natural and/or anthropogenic scenarios (Quay, 2010). Optimal policy decisions in such cases, then, refer to options that can guarantee robust system performance under considered "what-if" conditions (Wilby and Dessai, 2010).

As a further step toward improving the water resource management under uncertain future conditions, the objectives of this thesis are defined as the following:

1. To develop improved modeling tools that provide a better understanding of the overall and sectorial system performance under changing conditions;
2. To improve the assessment of system behavior under deep uncertainty, including better understanding of socio-economic and environmental trade-offs and overall system performance; and finally,

3. To establish an improved decision making framework that can provide new insights on future risks in system performance and assist in evaluating alternative planning decisions under uncertain water availability as well as policy and demand conditions.

The objectives highlighted above are pursued in an important water resource management system in western Canada with high significance for regional and national food and water security.

1.3 Case study

The Saskatchewan River Basin (SaskRB) in Saskatchewan is an example of a complex water resource system in Canada that has future management challenges under deep uncertainty. The system is developed around the South and North Saskatchewan Rivers (SSR and NSR), flowing to the region from the neighboring province of Alberta, and supports water allocation for various socio-economic, and environmental sectors. Hydropower and irrigated agriculture are key economic competitors in the system and have strategic importance for energy and food security. In the downstream part and before entering Manitoba, the SaskRB in Saskatchewan feeds the Saskatchewan River Delta (SRD), the largest inland delta in North America. SRD is an important ecosystem with endangered wildlife species and is home to First Nations communities (Partners for Saskatchewan River Basin, 2008). The flow from Saskatchewan to Manitoba must fulfill inter-provincial apportionment commitments. In simple words, the 1969 Master Agreement on Apportionment requires the Prairie Provinces to pass half of their natural flows to the downstream province (Prairie Province Water Board, 2015). With regard to this policy constraint, the system is not over-allocated and the ratio of annual consumptive water use to the annual flow in SaskRB in Saskatchewan is currently less than 20%. Various concerns, however, remain in system due to the large historical changes in the SRD flow regime, trade-offs between the irrigation and hydropower sectors, and the capacity to meet inter-provincial commitment during extremely dry conditions.

The future of the SaskRB in Saskatchewan is also confronted by challenges associated with changing water availability and socio-economic activities. Most importantly, surface water availability in Saskatchewan strongly depends on the incoming streamflow regimes of the SSR and NSR inflows (Pomeroy et al., 2005), which are subject to major changes. First, climate change has already affected the snowpack and glaciers of the Canadian Rockies, which provide the headwaters of both rivers. This has already changed the water availability regime in Alberta (see Rood et al., 2005; Rood et al., 2008; Shook and Pomeroy, 2012; Harder et al., 2015). In addition, anthropogenic effects such as irrigation and operation of major dams have significantly affected Alberta's streamflow regime (St Jacques et al., 2010). Such changes can potentially threaten water availability in Saskatchewan. Second, Saskatchewan is going through a major economic development in various water sectors such as potash, hydropower and irrigation, among which the latter is Saskatchewan's largest water project (Saskatchewan Government, 2015). In particular, Saskatchewan has investigated increasing the current irrigated area by 400% to enable agriculture to play a major role in global food security (Saskatchewan Ministry of Agriculture, 2015). This, in conjunction with changing inflows, might result in various sources of "stress" in the system, which can pose further challenges for provincial water resource management and the apportionment commitment.

Based on the above discussion, there are major water security questions in Saskatchewan: (1) How can changing water availability conditions under current and expanded irrigation levels impact future water resource management? (2) How much can Saskatchewan sustain irrigation expansion under changing streamflow conditions? (3) How can alternative policy decisions support expanding irrigation under changing water availability?

To address these concerns, certain technical developments are needed. First, an integrated water resource model should be developed that can describe various interactions within the system with a sufficient degree of details. This capability has not been previously available in operational Water Resources Management Model (WRMM; Alberta Environment, 2002). In fact, the current WRMM model ignores the linkage between irrigation demand and hydroclimatic drivers. In addition, WRMM does not account for economic aspects of water use and allocation as well as the associated trade-offs in the system. A new water resource model therefore, is required for more realistic representation of irrigation and for sectorial economic evaluation. Such a hydro-economic model can complement the existing WRMM model.

Second, likely scenarios of changing incoming flows to Saskatchewan should be projected. This is an extremely challenging problem. Most importantly, the main headwater contributions are from snowmelt runoff in the mountainous regions (Déry et al., 2009), which is subject to many sources of difficulties in modeling, even under historical conditions (Nazemi and Wheater, 2014a). In addition, future hydroclimatic projections are highly uncertain in the region and many studies projected the future flow regime of Alberta with a wide uncertainty envelope (e.g., Toyra et al., 2005; Byrne et al., 2006; Martz et al., 2007; Lapp et al., 2009). For instance, the North Saskatchewan Watershed Alliance (2008) used various GCMs to predict the future changes in annual water yield in the NSR. They found that while some climate models are estimating increases in annual yield ranging from 5% to 15%, other GCMs are predicting decreases from 3% to 23 % during the same period. Similarly, Pomeroy et al. (2009) used climate models to estimate the impacts of climate change on flow regime in Alberta. They found that the changes in mean SSR flow regime at Alberta/Saskatchewan border is -22% to 8%, with an average decrease of 8.5%. Last but not the least, current hydrological models often ignore the complex water resource management taking place in Alberta, which intensively regulates the headwater streamflow regime as SSR and NSR move toward Saskatchewan. Such hydrological models, at their best, can provide a notion of "naturalized flow" (Pomeroy et al., 2009) at the Saskatchewan border, which can be significantly different from the actual flow coming into the province.

Finally, a decision making framework is needed to evaluate alternative policy options that can result in more robustness and less vulnerability in the system performance under changing conditions. Such a framework is not available. In fact, there is a major gap in current decision making frameworks under uncertain futures, which is discussed in more details in Section 1.4.3.

1.4 State-of-the-art

1.4.1 Integrated water resource modeling

Integrated Water Resource Management (IWRM) is a vital need for sustainable development. IWRM should reflect competing human demands and their impacts on environmental needs (Loucks et al., 2005). This is more important under changing water availability conditions (Cosgrove and Loucks, 2015). For this purpose, various models based on either optimizing (e.g. Cai et al., 2002) or simulating (Marques et al., 2006) the system performance have been developed. Optimization models work based on maximizing economic benefit or minimizing the water deficit in the system; as a result, a precise picture of the system characteristics and constraints are required to guarantee optimal allocation (Harou et al., 2009). In contrast, simulation-based models focus on representing interrelationships in system components (Jakeman and Letcher, 2003; Cai et al., 2012; Varela-Ortega et al., 2011) and investigating the effects of possible changes on the hydro-economic performance of the system (Heinz et al., 2007; You et al., 2010; George et al., 2013).

Among various simulation environments used for model development, System Dynamics (SD; Forrester, 1961) is one of the methods, which facilitate representing the interactions among various components that affect the sectorial and/or overall system performance. SD models explicitly capture the feedback loops among system components and allow tracking the pattern of change in individual components and the whole system over time and space. Moreover, SD models allow integrating a wide variety of system aspects including policy, socio-economy, and natural processes into the analysis of complex water systems (Kelly et al., 2013). SD has been increasingly used in environmental and water resources studies (e.g. Ahmad and Simonovic, 2002; Simonovic and Li 2003; Elshorbagy et al., 2007; Madani and Mariño, 2009; Simonovic, 2009; Winz et al., 2009; Ahmad and Prashar, 2010; Davies and Simonovic, 2011; Gohari et al., 2013; Chen and Wei, 2014). For instance, SD has been used in assessing trans-boundary water allocation decisions (e.g., Gastélum et al., 2010), solving urban water resource management problems (e.g., Stave; 2003), as well as understating environmental consequences of policy decisions (e.g., Ewers, 2005; Saysel et al., 2002; Liu et al., 2008) – see Mirchi et al. (2012) for a detailed literature review. Considering the selected case study for this thesis, SD can be used as an excellent IWRM platform for representing the dynamic of irrigation demand based on hydroclimatic drivers and available soil water. This can improve understanding of the feedback processes in water demand and water allocation. This requires coupling the estimation of water demand and water allocation in a unified model structure.

1.4.2 Assessing water resource systems under changing water availability conditions

The common approach to assess the performance of the system under changing water availability conditions is based on a cascade of models and is called a "top-down" approach. In this approach, streamflow series are obtained from hydrological models that are forced with the downscaled meteorological variables of GCMs (Wilby, 2005). The level of detail in downscaled future climate variables can vary from a few realizations (e.g. Payne et al., 2004; Raje and Mujumdar, 2010; Eum and Simonovic, 2010; Mateus and Tullos, 2014; Robles-Morua et al., 2015) to multiple stochastic realizations obtained from weather generators (e.g. Dessai and Holmes, 2007; Borgomeo et al., 2014). Regardless, different downscaling techniques can result in significantly different projections at the scale relevant to water resource management (e.g., Harpham and Wilby, 2005; Chen et al., 2010). This can result in large climate projection uncertainty (Diaz-Nieto and Wilby, 2005; Salas et al., 2012). Hydrological modeling, as indicated above, is also subject to uncertainty. The total uncertainty, thus, is large and can propagate to the vulnerability assessment of water resource systems (Wilby and Harris, 2006; Kundzewicz et al., 2008).

In response to this challenge, “bottom-up” approaches were developed and implemented to assess the potential vulnerabilities in water resource systems without direct use of downscaled GCMs projections (e.g., Bryant and Lempet, 2010; Prudhomme et al., 2010). The main objective of the bottom-up approaches is to highlight possible vulnerabilities and to propose planning decisions that can perform acceptably over a wide range of plausible future conditions. As a result, adaptation policies based on this approach are not biased nor limited to the results of climate and hydrological models. The bottom-up framework includes various methodologies, including Robust Decision Making (Lempert et al., 2004) and Decision Scaling (Brown et al., 2011b). The main difference among various bottom-up assessments is related to the method, with which changing water availability conditions are realized (Herman et al., 2015). For example, Robust Decision Making samples multiple climate conditions stochastically from observed records or GCMs projections (Lempert et al., 2006; Groves and Lempert, 2007; Lempert and Collins, 2007; Groves et al., 2008). Conversely, in Decision-Scaling, system stress is represented through “vulnerability maps” that reflect overall system performance, without using climate projections (Brown et al., 2011a). These maps are then employed to identify critical climate conditions that cause system vulnerability.

Despite these developments, conventional bottom-up assessments still require hydrological models to convert the realized climate futures into estimated water availability conditions. As discussed, uncertainties in hydrological models can propagate into performance assessment of water resource systems (Brown et al., 2012). To overcome this, Nazemi et al. (2013) proposed a fully bottom-up approach to stochastically generate possible future water availability conditions without incorporating any hydrological model. In this approach, consistent with historical data and top-down projection, the flow regime is perturbed with respect to changes in the key streamflow characteristics such as annul flow volume and the timing of the annual hydrograph peak. Nazemi et al. (2013) visually demonstrated how changes in flow regime can cause failure in the considered water resource systems. The quality of this analysis, however, is still dependent on how well the flow conditions are reconstructed (Nazemi and Wheater, 2014a); and the limitations in flow reconstruction can propagate into assessment of state and performance of water resource systems (Nazemi and Wheater, 2014b).

1.4.3 Decision analysis under uncertain future conditions

The uncertainty in projecting the future water availability results in uncertainty in estimating the future system performance. This uncertainty can be represented as a probability distribution that describes the risk in system performance under changing conditions. Such risk assessments have been mainly applied in the context of climate-related variables, in which multiple GCM projections are used to provide a likelihood function for the critical climate conditions (Brown et al., 2012; Steinschneider and Brown, 2012; Brown and Wilby, 2012). For instance, Moody and Brown (2013) assessed the performance of regulation plans for the Upper Great Lakes under a wide range of climate conditions. Whateley et al. (2014) attempted to compare the robustness of different planning decisions under climate change uncertainties. They assessed how additional robustness can be gained in operating reservoirs considering new adaptation policies under changing climate. Ghile et al. (2014) used this approach to identify the system vulnerability given the changing climate conditions and new infrastructure plans in the

Niger River Basin in West Africa. Steinschneider et al. (2015a) superimposed probabilistic climate projections on the vulnerability maps in order to estimate the climate-related risks of water shortage. Most recent studies include assessing the impacts of both changing water availability and demand conditions on the risk in the system performance (e.g., Lownsbery, 2014). For example, Steinschneider et al. (2015b) synthetically generated a wide range of changing climate variables and used them to quantify the robustness of preselected planning alternatives under increasing water demands and uncertain climate futures, obtained using available climate projections.

Despite these developments, there are still major challenges. In fact, current risk-based frameworks mainly account for climate-related risk in the system performance, which is obtained in light of available GCM projections. Only a few studies such as Jeuland and Wittington (2014) have discussed the risk in system performance due to policy decisions, which might be implemented under different runoff conditions. However, a standard approach, with which the multiple risks in future system performance can be quantified, is not available. From a management perspective understanding the relative effects of single or jointly changing conditions can identify how various drivers can intensify or suppress the risk in system performance. Having such an assessment tool can result in selecting robust policies under uncertain future conditions. This is currently lacking.

1.5 Synopsis of the thesis

In response to research objectives, knowledge gaps, and the challenges identified in the SaskRB in Saskatchewan, three research manuscripts are presented in the following three chapters. Based on these papers, this thesis is summarized and concluded in Chapter 5.

Chapter 2 proposes an integrated simulation-based water resource system model for Saskatchewan. This model is developed in a SD environment. The Sustainability-oriented Water Allocation, Management, and Planning model ($SWAMP_{SK}$) combines irrigation and economic evaluation sub-models with a conceptual water allocation model. An advanced irrigation sub-model estimates irrigation demand as a function of climate driver, allocated crop water, and initial soil moisture content. The economic sub-model estimates the annual net benefit for various sectors including hydropower and irrigated agriculture, and can reflect trade-offs among competing water users. The performance of $SWAMP_{SK}$ is evaluated and verified with respect to observed records, as well as the existing WRMM model, used for operational purposes. The methodology that was used to develop this model is generic and can be applied in other regions. This manuscript has been published in the *Environmental Modelling & Software* Journal in 2014 – see the permission of reproduction in Appendix A.1.

Chapter 3 evaluates the impact of uncertain water availability, in conjunction with alternative levels of irrigation expansion, on the performance of the SaskRB system in Saskatchewan. The fully bottom-up approach proposed by Nazemi et al. (2013) is used to generate a wide range of feasible streamflow conditions at the Alberta/Saskatchewan border. The stochastically generated flow conditions correspond to possible changes in annual flow volume and peak flow timing. The ensembles of streamflow realizations as well as various options of irrigation expansion level are then fed to the developed $SWAMP_{SK}$. Ultimately, the performance of the system is comprehensively assessed and visualized using irrigated agriculture and hydropower economic net benefit, inter-provincial water apportionment commitment, as well as the flow regime in the SRD. Apart from this application, this paper has investigated the capability of Nazemi et al. (2013)'s algorithm in maintaining the statistical properties of the generated flows. This manuscript has been published in the *ASCE Journal of Water Resources Planning and Management* in 2015 – see the permission of reproduction in Appendix A.2.

Chapter 4 proposes a generic framework to quantify relative changes in the risk associated with the performance of water resource systems due to combinations of changing water availability, policy options, and irrigation expansion. In brief, using Empirical Cumulative Density Functions, obtained through multiple model simulations, the relative contributions of various changing drivers on system performance are quantified. It is shown that such a simple quantification can be used as an effective tool for decision making under uncertainty. This manuscript was submitted to the *Advances in Water Resources* in 2015.

Finally, **Chapter 5** summarizes the findings of this thesis and highlights the contribution of this research. The limitations of this effort and further suggestions for future developments are also given in this chapter.

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Chapter 2 - Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada

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Contribution of the PhD candidate

Conceptualization and development of the integrated water resource model was carried out by the PhD candidate. Dr. Amin Elshorbagy and Dr. Howard Wheater provided advice on various aspects of the work. The scenarios for testing the system behavior have been designed by the candidate with all co-authors providing guidance on the formation and the analysis. The text of the manuscript has been drafted by the candidate. Dr. Gober offered critical review and editorial guidance.

Contribution of this chapter to the overall study

This work was intended to construct an integrated water resource systems model that provides improved understanding of the causal relationships among underlying system elements and the whole system behavior in the SaskRB in Saskatchewan. The model, called $SWAMP_{SK}$, combines various sub-models, including detailed water allocation, irrigation demand and economic evaluation components in one framework, which allows highlighting the trade-offs among system components. Building and validating $SWAMP_{SK}$ is the core objective of this chapter. The model is consequently used in Chapters 3 and 4 for exploring the SaskRB's performance under changing conditions.

2.1 Abstract

Using a system dynamics approach, an integrated water resource system model is developed for scenario analysis of the Saskatchewan portion of the transboundary Saskatchewan River Basin in western Canada. The water resources component is constructed by emulating an existing Water Resources Management Model. Enhancements include an irrigation sub-model to estimate dynamic irrigation demand, including alternative potential evapotranspiration estimates, and an economic sub-model to estimate the value of water use for various sectors of the economy. Results reveal that the water resource system in Saskatchewan becomes increasingly sensitive to the selection of the evapotranspiration algorithm as the irrigation area increases, due to competition between hydropower and agriculture. Preliminary results suggest that irrigation expansion would decrease hydropower production, but might increase the total direct economic benefits to Saskatchewan. However, indirect costs include reduction in lake levels and river flows.

2.2 Introduction

Water resources globally are under pressure, mainly due to population growth, intensive socio-economic development and warming climate (Vörösmarty et al., 2000). The transboundary Saskatchewan River Basin (SaskRB) in western Canada is a key resource for the prairie provinces of Alberta, Saskatchewan and Manitoba, and an example of a complex water resource system that is facing these water security challenges (Gober and Wheater, 2013). The main river flows in the province of Saskatchewan are dominated by flows generated in the Rocky

Mountains in Alberta, which provide water to industry, agriculture and urban centres. Recent years have seen severe extremes of both flood and drought (Wheater and Gober, 2013), and due to the impacts of climate change and intense human regulation in Alberta, the future characteristics of these flows might change (Nazemi et al., 2013).

Increasing demands in the Province stem from population growth, large economic investments in mining, and agriculture. Agriculture is currently the major water demand, accounting for more than 56.3% of water withdrawal in Saskatchewan (Martz et al., 2007). The Saskatchewan Ministry of Agriculture has proposed a 400% increase in irrigated area to address global food security and stimulate economic development (Saskatchewan Ministry of Agriculture, 2015). This proposal presents potentially significant challenges for the maintenance of healthy ecosystems downstream, including the Saskatchewan River Delta (SRD), the largest inland river delta in North America, which includes multiple wetlands and lakes that have high ecological and cultural values for the resident First Nation communities (Partners for the Saskatchewan River Basin, 2008). In addition, Saskatchewan has inter-provincial commitments. The 1969 inter-provincial Master Agreement on Apportionment requires Alberta to pass half of the natural flows to Saskatchewan, which is in turn required to pass half of that flow and other natural flows in Saskatchewan to Manitoba (Prairie Province Water Board, 2013). Dealing with these problems and planning for the future of Saskatchewan needs an integrated water resource model that estimates agricultural water demand, includes impacts of climate change, and helps to investigate the economic benefits of policy decisions.

Various object-oriented simulation environments (e.g. Bayesian networks; System Dynamics; Agent-based models) are available to develop an integrated water resource model. These modeling approaches have many common points and model selection depends on the main purpose of the model application. Among these available approaches, System Dynamics (SD) explicitly captures the feedback loops among system components, and can be used by people with a minimal technical background, due to the capability of SD models to include different communication layers from user-interface to programming codes (Kelly et al., 2013). Thus, SD models are suitable for social-learning and understanding the modeling processes as well as involving dynamic feedback loops among the underlying components. SD has had wide application in environmental and water resources studies (e.g. Ahmad and Simonovic, 2006; Elshorbagy and Ormsbee, 2006; Winz et al., 2009; Hassanzadeh et al., 2012). For example, Simonovic and Fahmy (1999) used an SD approach to assess the long-term effect of alternative socio-economic development policies on a water resource system in the Nile River Basin in Egypt. Saysel et al. (2002) developed an SD model for southeastern Anatolia, Turkey to evaluate long-term environmental sustainability under alternative socio-economic and environmental scenarios. Ewers (2005) developed an SD model for the San Juan watershed in northwestern New Mexico (with extensions into Colorado, Utah and Arizona), including agricultural, municipal, and energy components and evaluated the effect of increasing power production on the required environmental flows in the system. Gastélum et al. (2009) used an SD approach in the Conchos Basin in Mexico to consider the effect of different water allocation policies on water delivery to the United States and agricultural production within the Basin. SD provides a simulation environment for place-based models that must be custom-built for the study area under consideration.

The objective of this study is to use SD to develop an integrated water resource management model for Saskatchewan that includes irrigation demand, and economic evaluation sub-models, and has the capability to investigate alternative environmental flow conditions. Furthermore, the model can be used in practice by decision makers. In a broad sense, the proposed model allows for Sustainability-oriented Water Allocation, Management, and Planning, and thus we refer to it as $SWAMP_{SK}$. The paper begins with an overview of the SaskRB water management concerns in Section 2.3, followed by a description of the $SWAMP_{SK}$ in Section 2.4, including water resource model construction in 2.4.1, development of several irrigation sub-models in Section 2.4.2; and cost-revenue analysis to inform policy makers about the productivity and economic value of water for various use sectors in Section 2.4.3. Model calibration and performance assessment are outlined in Section 2.5. Section 2.6 reports on the results of various growth and policy scenarios and final conclusions are given in Section 2.7.

2.3 Case Study

The SaskRB covers a large portion of the populated area in the Province of Saskatchewan (Figure 2-1). The schematic diagram of the water resource system in Saskatchewan is shown in Figure 2-2. The South Saskatchewan River (SSR) (bottom-left) after meeting a few demands in the South West of the province flows to Lake Diefenbaker. Water is allocated from Lake Diefenbaker to various water use sectors and a group of small reservoirs and delivers the regulated SSR flow through the major Coteau Creek hydropower station towards Saskatoon (center). The SSR after meeting multiple demands on its way, confluences with the North

Saskatchewan River (NSR) (top) and produces the Saskatchewan River (SR). The SR after meeting water for Codette and Tobin reservoirs flows to the SRD, and ultimately to Manitoba.

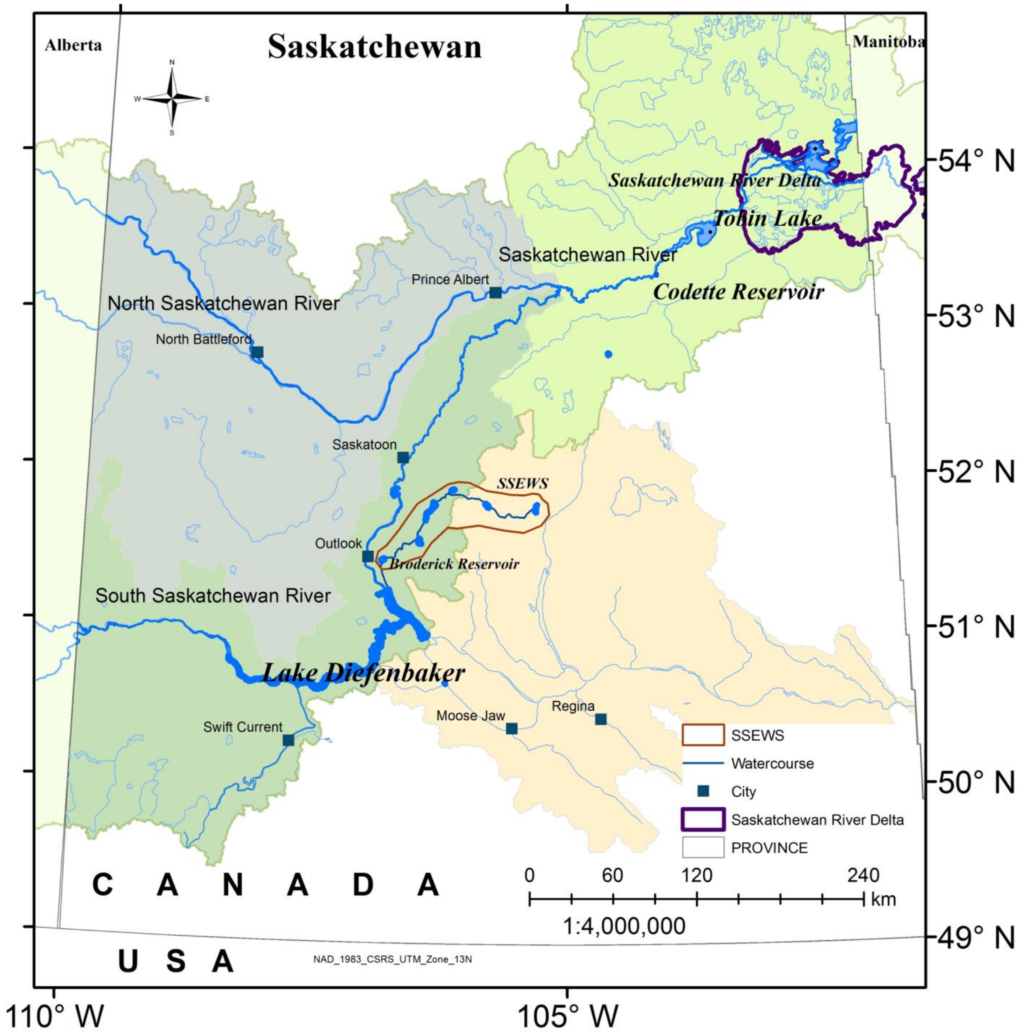

Figure 2-1 Saskatchewan River Basin in Saskatchewan (Map Produced by Jay Sagin, Global Institute for Water Security, 2013)

Lake Diefenbaker, the largest water body in the region, was built in 1959. Its maximum storage capacity is 9400 Million Cubic Meter (MCM). Lake Diefenbaker is a multiuse reservoir for hydropower production, supporting water for municipalities, irrigation, mining, recreation, and flood control and downstream flow regulation (SWSA, 2012b). The main discharge from Lake Diefenbaker is for the 186 MW Coteau Creek hydropower and subsequent downstream uses, accounting for 94% of water withdrawal, followed by evaporation from the lake (3%), water-use for irrigation, industrial, mining and municipal uses (2%) and the supplementation of flows in the Qu'Appelle River System (1%) (SWSA, 2012b), which supplies water for municipal requirements of the Cities of Regina and Moose Jaw, industrial requirements, irrigation in the Qu'Appelle Valley and the maintenance of the eight lakes in the Qu'Appelle River Valley for recreational uses. The management philosophy for this reservoir is to fill it during the high flow season of the spring Prairie snowmelt and the later runoff from ice melt at higher elevations combined with rainfall in Alberta headwaters, then deplete the stored water in fall and winter until the following spring, when the chance for refill returns (SWSA, 2012b). This annual operation supports flood control but does not support water availability capacity over a multi-year drought (SWSA, 2012b). The downstream Codette and Tobin Lakes mainly supply water for the 255 MW Nipawin and 288 MW E.B. Campbell hydropower stations, respectively – see the physical properties of the considered reservoirs in Appendix B, Table B-1.

Irrigated agriculture and hydropower are the major users of water in the Province (Government of Saskatchewan, 2013). Irrigation is seen as essential to diversify the rural economy and to stabilize crop production in this semi-arid Prairie region. Almost 25 percent of Saskatchewan's electricity comes from hydropower. Hydropower consumes little water but significantly changes the flow patterns of the river; reducing summer flows and increasing winter flows (Saskatchewan Electricity, 2013). Saskatchewan potash mines use a considerable amount of the Province's industrial water (Halliday, 2009).

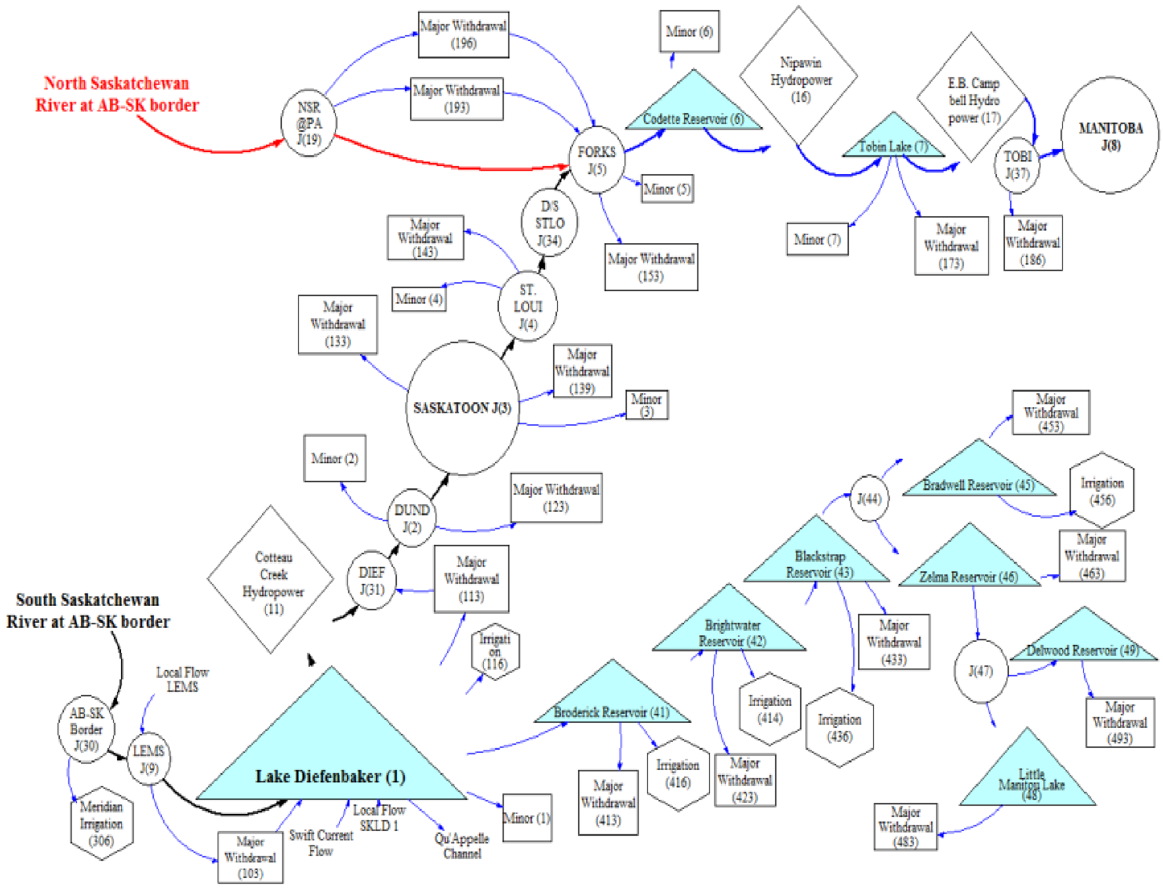

Figure 2-2 Simplified schematic of the water resource system in Saskatchewan from the Alberta/Saskatchewan border (left) to Manitoba (top-right). The South Saskatchewan River, North Saskatchewan River and Saskatchewan River flows are shown with thick black, red, and blue arrows, respectively. Remaining arrows represent other natural flows or diversion channels. Minor and Major withdrawals indicate the rural, municipal and industrial demands.

The province has a set of targeted objectives that relate to environmental flows during key seasons and at set locations. (1) Lake Diefenbaker is a crucial point in the system. The targeted water level in Lake Diefenbaker is above 551 m on May 1 to enable pumping water for irrigation areas, and between 555 and 555.3 m on July 1 to support recreational use and prevent flooding of the nests of Piping Plover, an endangered bird species; (2) environmental flow requirements stipulate that SSR flows toward the City of Saskatoon must maintain a minimum of 42.5 (m^3/s) to support downstream ecosystems and adequate sewage effluent dilution (Blackwell, 1963); (3) there should be adequate flow to support ecosystem and human health in the SRD, although precise figures are not provided; and (4) the Master Agreement on Apportionment to deliver half of natural flow and any flows that originate in Saskatchewan to Manitoba.

The water system is confronted by deep uncertainties about future water availability and demand. Canada's climate is changing (Zhang et al., 2000). As an example, Hao et al. (2013) showed that Canada has experienced concurrent increase in temperature and a decrease in precipitation which means significant change in river flows. Since more than 80 percent of flows in the SSR and NSR in Saskatchewan originate in Alberta (Pomeroy et al., 2009), any changes in the upstream SSR and NSR flows can significantly affect Saskatchewan's water resource system. Various studies have attempted to use different climate models as well as various hydrological models to project the NSR (e.g. Shepherd et al., 2010; North Saskatchewan Watershed Alliance, 2008) and SSR flows (e.g. Lapp et al. 2009; Pomeroy et al., 2009). However, the wide band of uncertainty associated with these studies' predictions dictates the need for a scenario-based assessment that can explicitly address uncertainty. Uncertainty also characterizes the future demand for water. Increasing demand comes from resource sectors such as agriculture and potash mining. The current irrigated area is around 40,000 hectares and there is potential to increase to more than 200,000 hectares (Saskatchewan Ministry of Agriculture, 2012). Saskatchewan Irrigation Projects Association (SIPA) (2008) provided a cost-benefit analysis of this expansion project and concluded that, at a 5% discount rate over 40 years, the increase in irrigation area would contribute as much as $35 billion to Saskatchewan's Gross Domestic Product. However, there is a need to evaluate associated impacts on other users, such as mining, recreational and other environmental uses, and the risks to supply under probable drought conditions.

2.4 SWAMP$_{SK}$ model development

The main inputs for SWAMP$_{SK}$ are apportioned SSR and NSR flows from Alberta, precipitation, temperature, industrial and municipal water demands, agriculture area, and the prices and costs associated with various activities. The main outputs from the model are reservoir water levels, water demand for agriculture, water availability for different sectors, and the economic value of water-use for each sector. Illustrating the interconnectivity of these variables informs decision-makers about how the water resource system works and highlights the likely future trade-offs that face them during periods of shortage. A Causal Loop Diagram (CLD) visually represents the feedback loops among the various system elements. The CLD between water resources, agriculture and economic models is shown in Figure 2-3. The interaction among factors within the water resources component and the influence of water resources on its sub-models are shown by blue arrows. The green arrows represent the factors affecting agricultural demand and the red arrows illustrate the factors affecting the economics of the agriculture, hydropower and mining sectors. The (+) and (-) signs in the figure demonstrate the direction of relationships. For instance, the positive relationship between Agricultural Water Demand and Water Supply for Agriculture shows that when agricultural demand increases, the water supply for agriculture increases. After drawing the CLD, the model variables were transformed into stocks, which characterize the state of the system and flows, which define rates that can change stock variables. The governing equations for states are represented by finite difference expressions and solved using standard numerical schemes (Ford, 1999).

2.4.1 Water resources model

Saskatchewan currently uses the Water Resources Management Model (WRMM) for guidance and research purposes. WRMM includes monthly data between 1928 and 2004, and information of the current system's physical properties, demand characteristics, and water allocation penalties. Water demands in this model are based on issued licenses, not actual/historical water demands. In addition, the operation of reservoirs is based on target criteria rather than the real operation of the reservoirs in the period of study. WRMM utilizes linear programming to allocate water to demands based on the system's physical boundaries and state, water availability, and operational policies. WRMM simulates the water resource system over a discrete set of time intervals. The operational policies are based on attempting to achieve the ideal release and storage to meet all water demands. In WRMM, each component is divided into a number of zones (e.g., a reservoir is divided into a few storage levels), each has its own penalty (costs) values. Water allocation priorities are modeled in WRMM based on these penalty values, which reflect the cost of not meeting each water demand (Nazemi and Wheater, 2014).

The SD simulation environment was used to emulate the water allocation procedures of WRMM. SD-based modeling has various advantages over WRMM. First, WRMM uses linear programming to allocate water; therefore, it assumes that the water allocation problem and all constraints can be described by linear functions of decision variables. However, water allocation problems in reality include non-linear interactions among decision variables, e.g., between allocated water in the previous time step and irrigation water demand in the current time step. In contrast, SD allows explicitly incorporation of non-linear feedback behavior and effects among system components over time. A second advantage of using a SD environment over WRMM is the flexibility and the transparency of the model structures. Finally, SD models allow managers and stakeholders to investigate and learn the effect of alternative scenarios on the system behavior by changing parameters and/or configurations of the system by adding new infrastructure, socio-economic variables, linkages, and feedback loops.

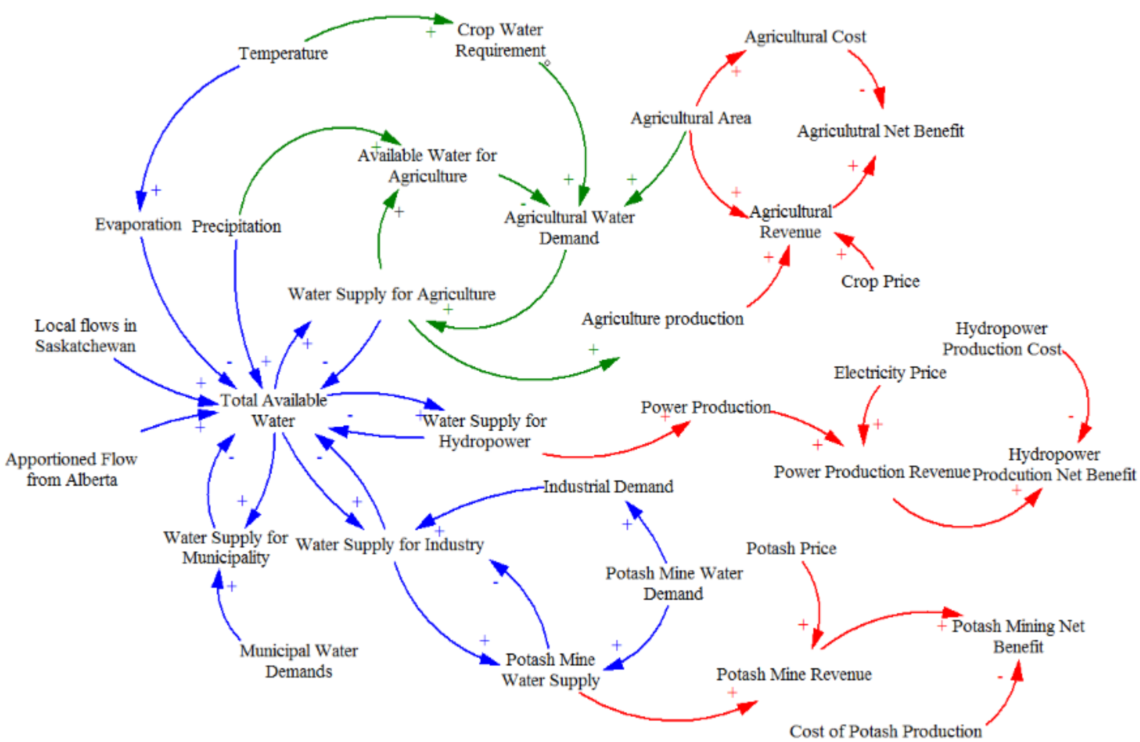

Figure 2-3 Causal Loop Diagram for the SWAMP$_{SK}$

These SD capabilities were fully used to construct SWAMP$_{SK}$. First, all required information of the system's physical properties such as reservoir minimum and maximum storage levels, water availability, and water demands were extracted from the WRMM model and used to construct the $SWAMP_{SK}$. Second, the same water allocation policy (the penalty functions) of WRMM was implemented in $SWAMP_{SK}$ using “If-then-else” functions. The simplified stock-flow diagram for Lake Diefenbaker is shown in Figure 2-4. The inflows to Lake Diefenbaker are shown on the left and bottom-left, and water demands are shown on the right. The spilled water and Cotteau creek hydropower station discharges, which deliver water toward Saskatoon, are shown at the top. The stock-flow diagram of Lake Diefenbaker represents a set of equations for system relationships. Equation 2.1 represents the water balance:

$$S(t_n) = \int_{t_0}^{t_n} \left[P(t) + INF(t) - E(t) - SP(t) - REG1(t) - REG2(t) \right] dt + S(t_0) \tag{2.1}$$

where t is time (months) between t_0 and t_n ($t_0 \leq t \leq t_n$), *S* is storage, *P* is precipitation, *INF* is inflows to the lake, *E is* evaporation, *SP* is spill from the reservoir spillway, *REG1* is total withdrawal for a set of major demands, excluding hydropower (i.e. Minor (1), Major (113), Qu’Appelle Channel, Broderick Reservoir (41), and Irrigation (116)), and *REG2* is withdrawal for hydropower (Figure 2-2). In the water allocation process, maintaining the minimum flow requirement can be achieved by delivering water to Coteau Creek hydropower station, as it is then transmitted downstream.

Total available water is estimated for Lake Diefenbaker at each step. Sorted penalty values for the reservoir’s storage zones and water use sectors demand zones indicate that the *REG1* water demands have the highest penalty values, followed by the operating zone for Lake

Diefenbaker levels and then hydropower demand. Only minimum water storage levels in Lake Diefenbaker have higher penalty values than the *REG1* water demands. These latter demands must be first fully satisfied up to the time that water in Lake Diefenbaker reaches its minimum water storage level. The individual penalty values of sectors in *REG1* assign priority to Minor (1), followed by Major withdrawal (113), Qu'Appelle Channel, Broderick Reservoir (41), and then irrigation (116) (Figure 2-4). After meeting water demand for all of the *REG1* needs, the Lake Diefenbaker water level is compared to its ideal level. The amount of water delivery to the hydropower station is decided based on the lake water level. If the lake level is above the ideal, the amount of water above the ideal level is delivered to the hydropower station. However, the delivered amount must not be less than the downstream minimum flow requirement. If the lake level, after meeting the *REG1* needs, falls below the ideal level, only water for the downstream flow requirement is allocated to the hydropower station.

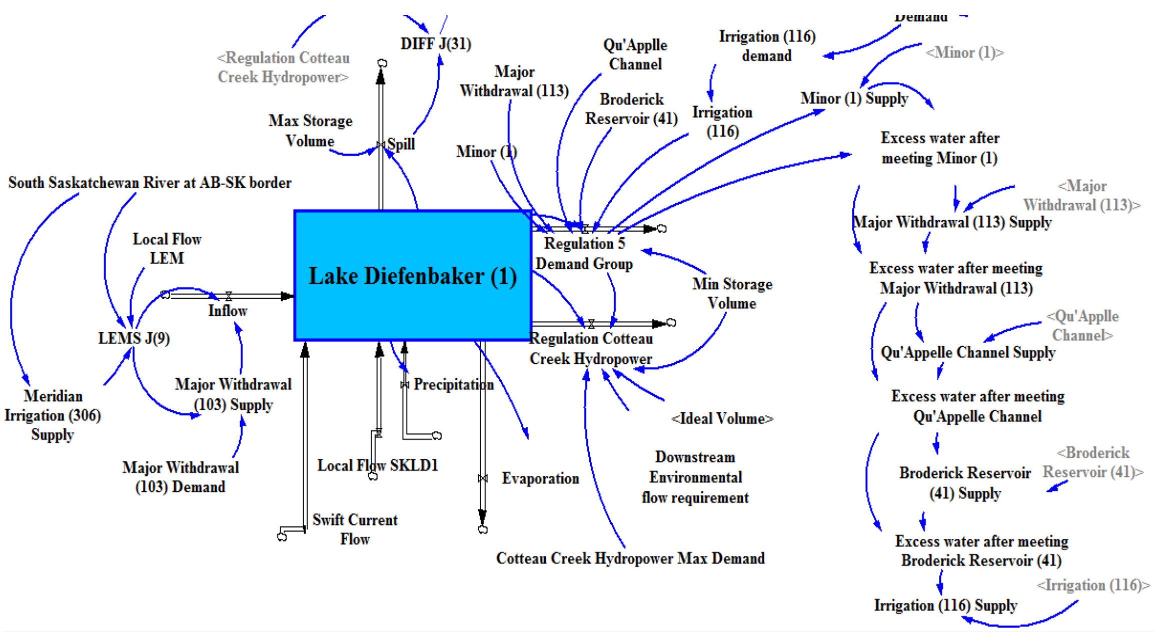

Figure 2-4 Stock-flow diagram for Lake Diefenbaker

2.4.2 Irrigation demand

The main crops in Saskatchewan are alfalfa, wheat, canola, barley silage, grass, pea, and potato (Martz et al., 2007). The total annual crop water requirement for these crops depends on climate conditions but typically ranges from 380 to 620 mm for the growing season (Irrigation Crop Diversification Corporation, 2008). In the WRMM model for Saskatchewan, a key assumption is that the total irrigation demand is 304 mm and does not vary annually. Evaluating the consequences of irrigation expansion proposals requires a reliable irrigation demand model that accounts for the effect of antecedent soil moisture and meteorological variables such as precipitation and temperature on soil moisture (Gueneau et al., 2012). Therefore, a monthly irrigation model developed by the U.S. Department of Agriculture's Soil Conservation Service (SCS) (USDA, 1970) was utilized in this study. Since a long-term objective of our modeling effort is to reduce the temporal scale of the model from monthly to daily time step when daily data are available, the daily irrigation demand model (IDM) developed by Phoenix Engineering Incorporation in Alberta (Government of Alberta, 2013) and used by the Saskatchewan Ministry of Agriculture to calculate irrigation demand was also used here. In both models irrigation demand is estimated dynamically by considering the climate variables, antecedent soil moisture and the crop water availability. The main difference between these two models is in the way their equations convert precipitation to effective precipitation to meet crop water requirements. The IDM uses empirical equations suitable for the Prairies, whereas SCS’s model equations are based on a 50-year data analysis of different locations in the United States, ranging from arid to humid climates. Reference evapotranspiration, crop evapotranspiration, and irrigation models are explained in the following sub-sections.

2.4.2.1 Reference evapotranspiration and Crop evapotranspiration

Reference evapotranspiration (ET_0) can affect estimates of water resource management practices in the region (McKenny and Rosenberg, 1993). ET_0 can be estimated by the Penman-Monteith equation with high accuracy, but using this equation requires data of various types of meteorological variable that may not be available in all regions. Required data also may not be available from all GCMs for analysis of climate change impact on irrigation demand (Farmer et al., 2011). Even if data can be extracted from some GCMs, Chun et al. (2012) showed that there is large uncertainty associated with the derived set of meteorological variables for Penman-Monteith calculations.

Hence simple equations that require fewer meteorological variables are commonly used to estimate ET_0 (Allen et al., 1998). Farmer et al. (2011) quantified/compared simple equations suitable for different locations in the globe. They compared ET_0 estimated by Penman-Monteith with the Hargreaves and modified Hargreaves equations, and empirical equations derived based on their own work for different seasons and for seven regions across the globe. They found that equations shown in the ET1 category in Table 2-1 present the closest results to the Penman-Monteith equation for regions including Saskatchewan. In Table 2-1, R_a, T_{avg}, T_D, P, Δ, e_a and u_2 are extraterrestrial radiation, mean monthly air temperature, difference between maximum and minimum air temperature, precipitation, slope of saturation vapor pressure-temperature curve, actual vapor pressure, and wind speed at 2-m height, respectively – see the monthly input data in Appendix B, Figure B-1. Maulé et al. (2006) used ET_0 equations of Liancre, Baier-Robertson, and Hargreaves-Samani for the Canadian Prairies. They also developed appropriate empirical ET_0 equations for this region (Table 2-1). The result of their study shows that, among available ET_0 equations, the Hargreaves-Samani equation was closest to Penman-Monteith, followed by Baier-Robertson and then Liancre. However, all equations were less accurate than the empirical equations developed by Maulé et al. (2006). Among their developed empirical equations, ET5 shows a higher accuracy, followed by ET4, ET3 and then ET2. The reason is that the more climatic data used in the model, the more accurate was the estimated ET_0. All five ET_0 equations shown in Table 2-1 were used for our study as options within the $SWAMP_{SK}$. Since these equations were obtained either based on the Prairies' meteorological data or from regions with similar climatic characteristics, it was assumed that they can estimate ET_0 in Saskatchewan with reasonable accuracy, given inherent data and process uncertainties. The required meteorological data were obtained from Environment Canada for stations closest to the irrigation areas.

Table 2-1 Reference Evapotranspiration models, ET1 (Farmer et al., 2011) and ET2 to ET5 (Maulé et al., 2006)

ET1	$ET\_1\_May = 0.0023 \times 0.408 \times R_a \times (T_{avg} + 17.8) \times T_D^{0.5}$
	$ET\_1\_June\_July\_August = 0.0013 \times R_a \times (T_{avg} + 17) \times (T_D - 0.0123 \times P)^{0.76}$
	$ET\_1\_September = 0.0019 \times 0.408 \times R_a \times (T_{avg} + 21.0584) \times (T_D - 0.0874 \times P)^{0.6278}$
ET2	$ET\_2 = 0.0023 \times 0.355 \times R_a \times (T_{avg} + 24.4) \times T_D^{0.5}$
ET3	$ET\_3 = 0.134 \times T_D + 0.0109 \times T_{avg} + 0.708 \times \delta \times R_a - 0.669$
ET4	$ET\_4 = 0.051 \times T_D + 0.131 \times T_{avg} + 0.846 \times \delta \times R_a - 3.18 \times e_a + 1.28$
ET5	$ET\_5 = 0.077 \times T_D + 0.114 \times T_{avg} + 0.832 \times \delta \times R_a - 2.77 \times e_a + 0.269 \times u_2 + 0.053$

Crop evapotranspiration (ET_c) was obtained from Equation 2.2, where K_c is the crop coefficient. K_c values for various crops were obtained from Cuenca (1989) and converted to monthly values for the growing season – see the crop properties in Appendix B, Table B-2 and Figure B2. The growing season in Saskatchewan starts from May and for most crops ends in September. Following Gastélum et al. (2009), it was assumed that Actual Evapotranspiration (AET) is a linear function of ET_c and depends on Field Capacity (FC) (mm) and Wilting Point (WP) (mm).

$$ET_c = K_c \times ET_0 \tag{2.2}$$

$$AET = ET_c \times \frac{SM - WP}{FC - WP} \tag{2.3}$$

2.4.2.2 Irrigation model

Soil Moisture (SM) modeling components were constructed for the above-mentioned seven crops. The maximum soil depth was assumed to be the maximum crop's root depth. FC and WP point are the maximum and minimum thresholds for soil moisture content. The irrigation demand (ID) is an amount that brings the soil moisture water content to FC, so that AET becomes equal to ET_c. The model formulation does not account for drought tolerance of crops (e.g. changes in leaf stomatal closure) and therefore changes in crop productivity is the function of water stress. Total irrigation demand (*TotalID*) is calculated based on the *Crop Area* and the *Irrigation efficiency* using Equation 2.4. Similar to the WRMM, irrigation efficiency is assumed to be 75% in $SWAMP_{SK}$.

$$TotalID = \frac{\sum_{i=1}^{7} ID_i \times Crop\ Area_i}{Irrigation\ \ efficiency} \tag{2.4}$$

2.4.2.2.1 SCS Irrigation Model

The stock-flow diagram for the irrigation demand model of alfalfa is shown in Figure 2-5. Meteorological variables (top-left) influence the ET_c. The amount of ET_c affects the amount of effective precipitation (bottom-right). Effective precipitation affects the amount of soil moisture (center). The amount of soil moisture affects the irrigation demand which in return influences the irrigation water supply. The amount of water supply influences soil moisture (center). Soil moisture and Et_c in return affect the actual evapotranspiration (top-center) and crop yield (top). Soil moisture at each time step $SM(t)$ (mm) is a function of its moisture at previous step $SM(t_0)$, effective precipitation $P_{eff}(t)$ (mm), irrigation supply $IS(t)$ (mm), actual evapotranspiration $AET(t)$ (mm) (Equation 2.5). Effective precipitation is the amount of precipitation that contributes to meet crop water requirements and does not contribute to produce runoff or drainage below the root zone (USDA, 1970). Effective precipitation cannot exceed the rate of crop evapotranspiration and total precipitation, and was calculated using Equations 2.6, 2.7, and 2.8 (Cuenca, 1989).

$$SM(t_n) = \int_{t_0}^{t_n} \left[P_{eff}(t) + IS(t) - AET(t) \right] dt + SM(t_0) \tag{2.5}$$

$$f(D) = 0.53 + 0.016 \times D - 8.94 \times 10^{-5} \times D^2 + 2.32 \times 10^{-7} \times D^3 \tag{2.6}$$

$$P_{efec} = f(D) \times (1.25 \times (P_t)^{0.824} - 2.39) \times 10^{(0.000955 \times ET_c)} \tag{2.7}$$

$$P_{eff} = \min\,(P_{effec}, ET_c, P_t) \tag{2.8}$$

where D is depth of soil moisture storage (mm), $f(D)$ is the soil water storage factor (mm), and P_t is total precipitation (mm).

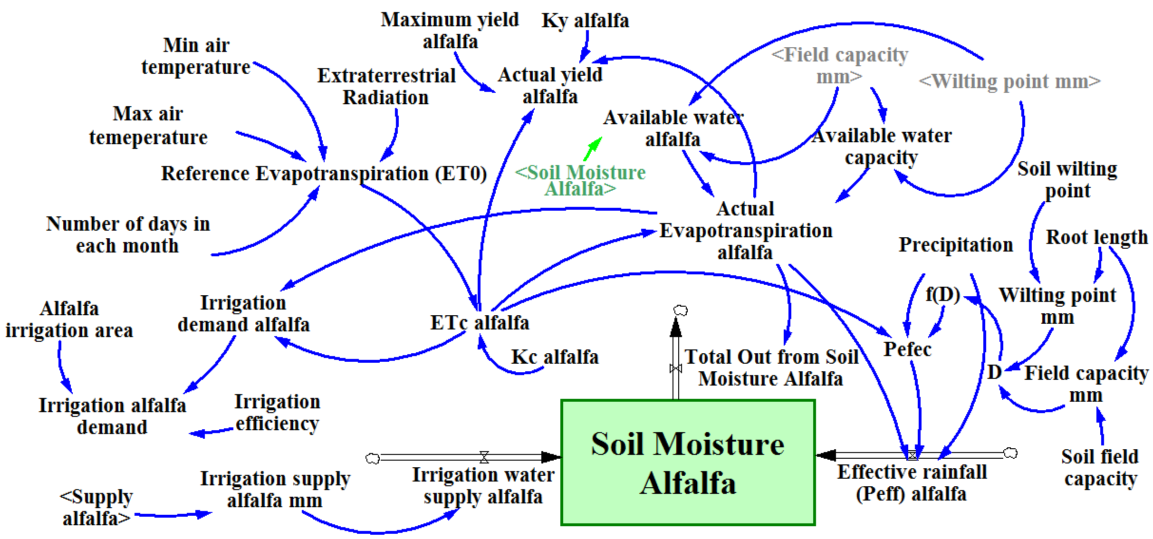

Figure 2-5 Stock-flow diagram of irrigation demand modeling component for alfalfa

2.4.2.2.2 IDM Irrigation Model

Although IDM is a daily timescale model, a simplified version of IDM, appropriate for monthly timescale processes, was used here. Using this model, the SM budget is as follows:

$$SM(t_n) = \int_{t_0}^{t_n} [P(t) + IS(t) - AET(t)] - Excess\,Water]\,dt + SM(t_0) \quad (2.9)$$

In IDM, *Excess water* (mm) is a portion of rain that does not contribute to crop water requirement and it was calculated using Equation 2.10. Estimation of AET is similar to SCS method. For more detail, see Government of Alberta (2013).

$$Excess\,Water = SM + P + WP - 1.1 \times FC \quad (2.10)$$

2.4.3 Economic evaluation

As mentioned in Section 2.3, irrigated agriculture, hydropower, and potash mining are key water-use sectors in the Basin. In the one hand, any development/policy decisions about these sectors can influence water availability in the Province; on the other hand, any changes in the water availability of the Province, e.g. changes in flows, can affect the productivity and economic viability of these sectors. By considering the amount of water used for a unit production of potash, hydropower, and crops, and by having the costs and benefits of the production, the economic value of water within each production was approximated. It should be noted that in our analyses, it was assumed that the prices and costs of production have fixed values. This means that the economic value of water does not change in response to other environmental and socio-economic factors, such as drought, water scarcity, and market changes related to other water-related products and services; e.g., food and energy. This narrows the scope of the economic component of the model to a financial analysis that can be improved by estimating varying water values through incorporating the effect of various factors mentioned earlier. It is also acknowledged that other values such as environmental flow requirements do not have costs attributed to them at this stage of model development. They are considered qualitatively in the analysis.

In order to produce one thousand tons of potash on an annual timescale, shaft and solution potash mines use approximately 0.00079 to 0.00137 MCM and 0.00553 MCM of water, respectively (SWSA, 2012a). The power production relationship with water flow for each month is shown in Equation 2.11, where P is power generated (MW), Q is flow in hydropower channel (m^3/s), H is the head available for power generation (m), HL is head loss at the rated head and flow (m), and TE and GE are turbine and generator efficiencies at rated head and flow.

$$P = \frac{Q \times (H - HL) \times TE \times GE \times 9.907}{1000} \tag{2.11}$$

Annual crop yields can be estimated using Equation 2.12 (FAO, 2002): where Y_i is the actual crop yield, $Ymax_i$ is the maximum crop yield in Saskatchewan (Table 2-2), and k_{ij} is the yield response factor *i* at the growing stage *j* (Allen et al., 1998). It should be acknowledged that, using this equation yield response is only a function of water stress, assuming that other aspects of plant physiology are constant (Kloss et al., 2013).

$$Y_i = Ymax_i - Ymax_i \times \sum_j k_{ij} (1 - \frac{AET_{ij}}{ET_{c\,ij}}) \tag{2.12}$$

Table 2-2 Information about major crops (irrigated area, and maximum yield, total cost, and price were obtained from Martz et al. (2007), and Irrigation Crop Diversification Corporation (2012))

Crops	Irrigated area (acre)	Maximum yield (ton/ha)	Total cost($/ha)	Price ($/ton)
Potato	2773	14	2651	440
Grass	6973	5	472	125
Silage	6973	16	424	60
Alfalfa	26381	5	361	85
Pea	6047	1.9	347	312
Canola	6301	1.6	472	495
Wheat	28565	2.2	417	252

The cultivation cost for each crop includes multiple variables such as costs of seeds, fertilizer, fungicide, insecticide, herbicide, hired labor, equipment fuel, pumping, property taxes, and crop insurance. Total costs and prices of production for each crop are shown in Table 2-2 and were based on discussion with grain marketing companies and farm supply retailers (Irrigation Crop Diversification Corporation, 2012). Costs in the hydropower sector include maintenance and repair. The mining costs include the cost of operation, maintenance and repair costs. Total price and cost of production values for mining, and hydropower are shown in Table 2-3. For future analysis, Net Present Values (NPV) is calculated by converting future costs and revenues to the present day values. A discount rate of 5% was assumed, similar to SIPA (2008); however, using VENSIM DSS (Ventana Systems, 2003), the sensitivity of NPV to discount rates can be visually presented for decision-makers.

Table 2-3 Costs and prices used for hydropower ($/MWh) and mining ($/ton) in 2012 (References for hydropower and mining are personal communication with Sandeep Kalra in Saskpower, and Kelly Freeman in Potashcorp, respectively)

Sector	Total cost ($/unit of production)	Revenue ($/unit of production)
Hydropower (MWh)	4.3	119.5
Mining (ton)	105	420.51

2.5 Model Performance Assessment

This section describes the qualitative and quantitative performance assessment of the $SWAMP_{SK}$. The structure and behavior of this SD model were tested to ensure that interrelationships among underlying elements of the model follow logical explanations and are not erroneous. Since one of the tasks of this study was to emulate the WRMM model, the performance of $SWAMP_{SK}$ with respect to the WRMM was assessed using a direct comparison of model results (scatter plot) and multi-criteria statistical performance metrics of the Root Mean Squared Error (RMSE), the Mean Absolute Relative Error (MARE) and the correlation coefficient (R). The scatter plot represents how the model overestimate/underestimates the observed values; the RMSE shows the size of discrepancy in the predictions with giving high weights to large errors; the MARE shows the error over the whole range of values, ignoring the magnitude of the state variable; and the R shows how the values of both models are linearly related. Thus, each of these measures presents useful information about the model performance and all combined can represent the model's overall accuracy. These performance criteria are commonly used for the model performance evaluation in the literature (Bennet et al., 2013).

The structural tests (both direct and structure-oriented behavior) and behavior pattern tests suggested by Barlas (1996) has been used for qualitative performance assessment of this SD model. To perform a direct structural test, the model structure was checked against knowledge about the real system. For this purpose, the logical relationships among variables (e.g. water allocation processes), and the dimensional consistency (e.g. units) in the $SWAMP_{SK}$ were verified. Structure-oriented behavior testing indirectly checks the model's structural accuracy by testing the system's behavior patterns. Various sensitivity analyses were conducted for this test. For instance, the patterns of changes (increase/decrease) in the Lake Diefenbaker water level with respect to the changes in its upstream flow values i.e. under extremely wet, dry and normal conditions were assessed to ensure Lake Diefenbaker simulations produce a reasonable behavior pattern. After verifying the structural accuracy of the model, the behavior of the $SWAMP_{SK}$ was tested using a reference mode, which shows the overall pattern of system behavior over time. For this purpose, each reservoir's reference mode was described by having overall knowledge about its operational policies (e.g. the historical information about the pattern of emptying and refilling of Lake Diefenbaker within a year). The Lake Diefenbaker and other reservoirs' reference modes were compared with their simulated behavioral patterns.

In order to quantitatively assess the performance of $SWAMP_{SK}$, its performance for the whole simulation period was evaluated by comparing the model results with WRMM (Label (I) in Table 2-4). Critical points for assessing model accuracy in simulating the real system are Lake Diefenbaker, Saskatoon, Codette reservoir, and Tobin Lake. As Lake Diefenbaker regulates the SSR flow coming from Alberta to Saskatchewan, these points can sufficiently represent the model accuracy for the whole system from the Alberta/Saskatchewan border to the Saskatchewan/Manitoba border. Lake Diefenbaker's water levels, reservoir releases, and hydropower production illustrate the state of the system almost at the start of the water resource system in Saskatchewan. Representing flow at Saskatoon is also important because Saskatoon is located in the centre of Saskatchewan's water resource system, and flows released from Lake Diefenbaker reach Saskatoon after meeting various demands. So, if we can accurately simulate the system up to this point, it means we are simulating almost half of the system correctly. Nipawin hydropower production indicates the system performance after the Codette reservoir and shows the system's behavior after the confluence of the SSR and NSR. Flow below Tobin Lake shows the system's performance almost at the end of the system, where the simulation results quantify the flows toward the downstream province of Manitoba. Similarly, understanding how both models behave in meeting the city of Saskatoon's demand and the agricultural demand is also crucial for our model performance evaluation. Low values for MARE and RMSE and high R values for these locations imply that the $SWAMP_{SK}$ emulates the WRMM well.

However, the $SWAMP_{SK}$ performance in emulating WRMM can be improved by calibrating the Coteau Creek hydropower regulation of $SWAMP_{SK}$ with respect to its values in the WRMM model. The calibration period includes 67 percent of the data and the validation period entails the rest. Hydropower regulation (*REG2*) in Equation 2.13 can be represented with intercept and slope parameters i.e. *A*REG2+B*, where under normal conditions *A* and *B* are one and zero, respectively. Other variables in Equation 2.13 are explained in Section 2.4.1. The Powell hill climbing calibration technique of Vensim DSS was used to find the optimum values for *A* and *B* in such a way that the sum of squared difference between power production of $SWAMP_{SK}$ and WRMM is minimized. The Powell hill climbing algorithm uses conjugate directions to search for the optimum parameters in a multidimensional space by repeatedly using single dimensional optimization and it exhibits quadratic convergence speeds (Powell, 1964). This embedded method in Vensim is considered to be computationally efficient and simple, as it does not require first-partial derivatives of the objective function (Sarmiento, 2010). The obtained values for *A* and *B* by calibration were 0.93, and 57.73 MCM, respectively.

$$S(t_n) = \int_{t_0}^{t_n} \left[P(t) + INF(t) - E(t) - SP(t) - REG1(t) - (A \times REG2(t) + B) \right] dt + S(t_0) \qquad (2.13)$$

To improve the $SWAMP_{SK}$ performance for each month of the year, monthly calibration parameters for *A* and *B* were also found. The performance results of the model for the validation (unseen data) with two and 24 calibration parameters are also presented in Table 2-4. Clearly calibration improved the emulation process. While calibration with a large number of parameters improves the accuracy of the $SWAMP_{SK}$ emulating WRMM, using the statistical “F” distribution test for model selection showed that, the error reduction in Model (III) relative to Model (II) is not considerable. Hence, for our modeling work, the $SWAMP_{SK}$ with two calibration parameters for Coteau Creek hydropower regulation (i.e. Model (II)) was selected.

The performance of $SWAMP_{SK}$ in emulating WRMM is shown for some critical locations in Table 2-4. The scatter plot and time series of $SWAMP_{SK}$ and WRMM show results of the models between 1928 and 2004 using the WRMM irrigation demand in $SWAMP_{SK}$ for comparability (Figures 2-6 and 2-7). Results show that $SWAMP_{SK}$ emulates WRMM with high accuracy. However, there is a difference in power production of the Nipawin Station, between the two models, related to a difference between the simulated flow of $SWAMP_{SK}$ and WRMM at that point. The $SWAMP_{SK}$ and WRMM modeling values for Lake Diefenbaker are similar. Only in a few cases, $SWAMP_{SK}$ underestimates the water level of Lake Diefenbaker of WRMM. Apart from some outliers, the discrepancy between the simulated SSR flows at Saskatoon by both models is small. Performances of both models converge in downstream.

Figure 2-8 shows the mean ET_0 values for the growing season obtained by using five ET_0 equations. ET3 results in the highest value for July and August among all models. After ET3, ET5, which uses the maximum number of climate variables, results in the highest ET_0 values for all months, followed by ET4, ET2, and ET1. Figure 2-8 also implies that among the models that need a small number of climate variables (i.e. only temperature and extraterrestrial radiation), ET3 produces the highest values compared to ET2 and ET1. Another observation from Figure 2-8 is that all of the locally developed equations (i.e. ET2, ET3, ET4, and ET5) produce high values compared to the equations of Farmer et al. (2011); i.e., ET1.

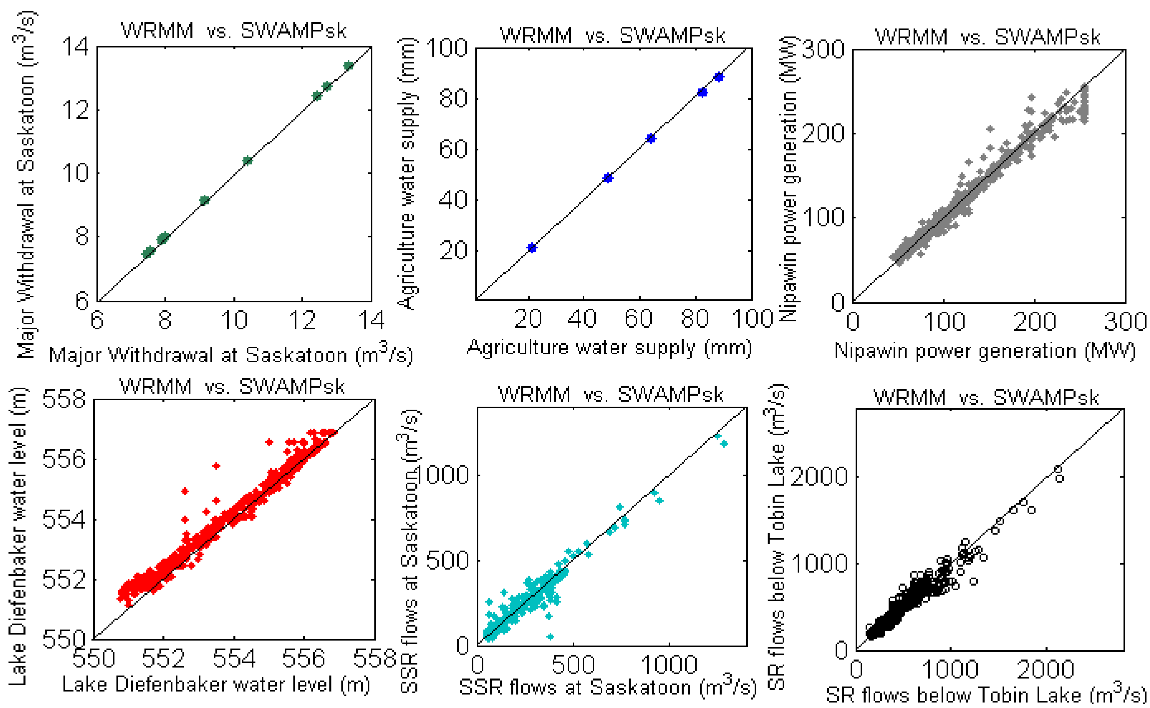

Figure 2-6 Scatter plot between WRMM (Y-axis) and SWAMP$_{SK}$ (X-axis) for critical points in the system after calibration with 2 parameters

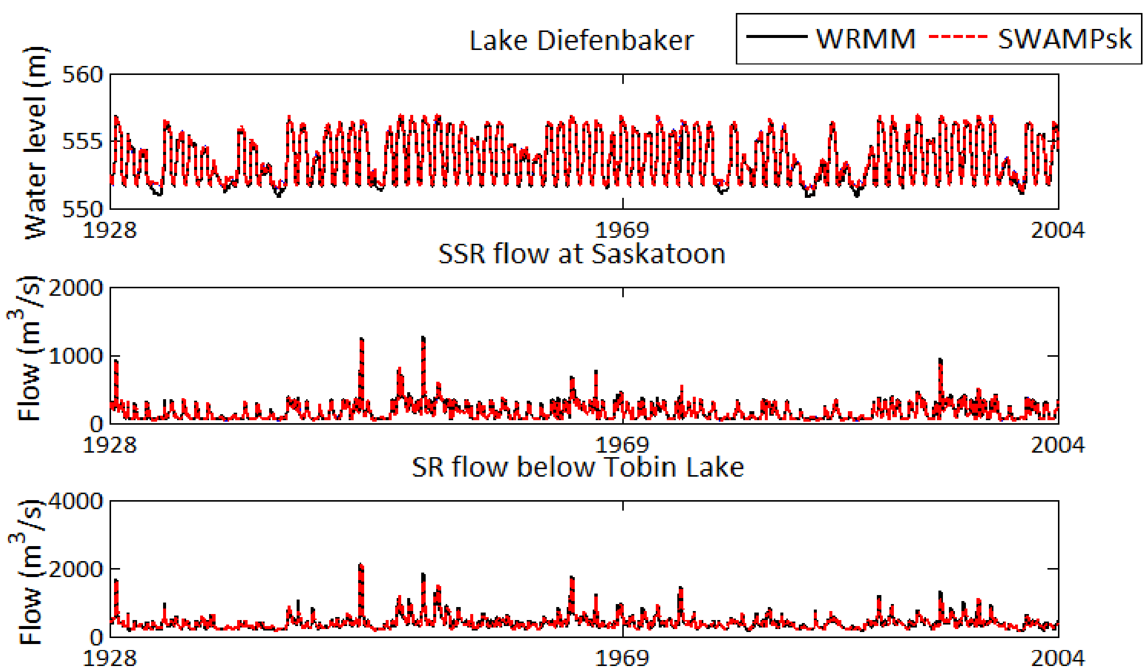

Figure 2-7 Simulated system performance in Lake Diefenbaker, Saskatoon, and below Tobin Lake using SWAMP$_{SK}$ versus WRMM

Table 2-4 The SWAMP$_{SK}$ statistical performances compared to WRMM for the entire simulation period before utilizing calibration, and for calibration and validation datasets using 2 and 24 parameters, respectively.

Label	Description/Performance		Coteau Creek hydropower			SSR flow at Saskatoon			SR flow below Tobin Lake		
			RMSE (MW)	MARE	R	RMSE (m^3/s)	MARE	R	RMSE (m^3/s)	MARE	R
(I)	SWAMP$_{SK}$ before calibration	Simulation period	16.37	0.14	0.95	38.62	0.16	0.96	63.65	0.11	0.95
(II)	SWAMPSK after 2-parameter calibration	Calibration	12.78	0.11	0.97	30.91	0.11	0.98	56.45	0.07	0.97
		Validation	10.1	0.11	0.98	24.45	0.11	0.98	49.23	0.08	0.97
(III)	SWAMPSK after 24-parameter calibration	Calibration	11.74	0.10	0.97	29.01	0.11	0.98	54.34	0.07	0.97
		Validation	9.54	0.10	0.98	23.6	0.11	0.98	43.97	0.07	0.97

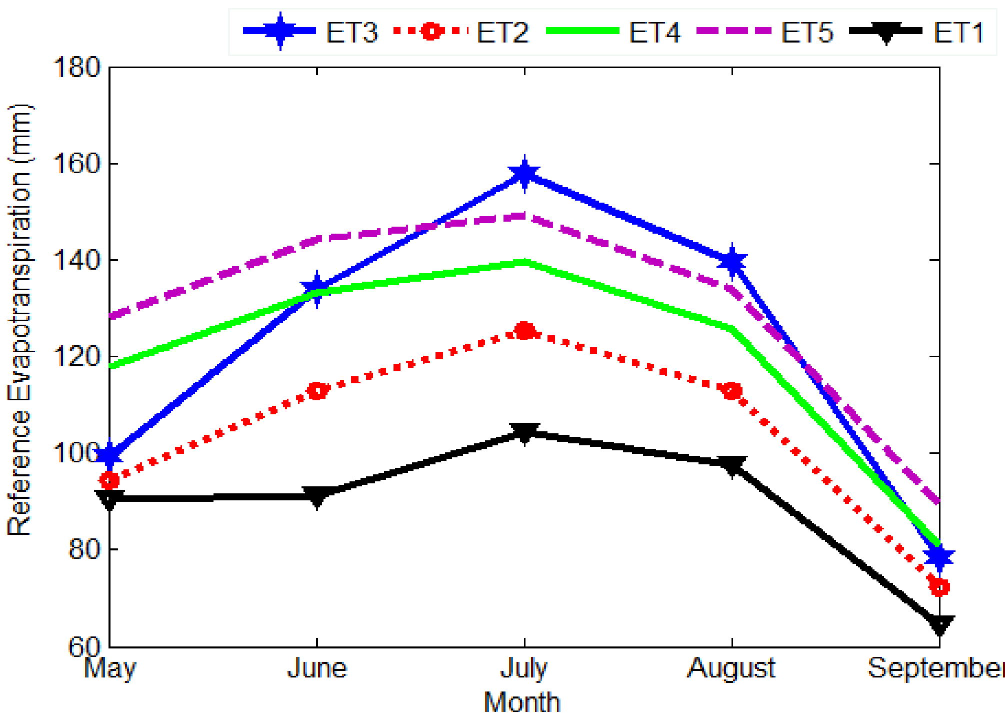

Figure 2-8 Mean Reference Evapotranspiration (ET_{0}) for growing season using different ET_0 equations

Figure 2-9 demonstrates the total irrigation demand (TID) in mm for combinations of the ET_0 equations and two irrigation demand models (SCS and IDM). TID values were obtained after linking the irrigation demand model component to the water resources model component. In all cases, TIDs were fully satisfied by the system's water model. Figure 2-9 shows that the constant irrigation demand usage in WRMM may overestimate the irrigation demand for wet years and underestimate the demand for dry years. Irrigation demand estimation is more sensitive to the ET_0 equation selection rather than the choice of soil moisture models (Figure 2-9). Mean TID values found by using IDM are higher than SCS model for all five ET_0's. Among the different ET_0 estimates, on average ET5 estimates higher TID followed by ET3, ET4, ET2, and then ET1. The TID values resulting from ET1 and SCS (SCS-ET1) and ET5 and IDM (IDM-ET5) have the lowest and highest values, respectively.

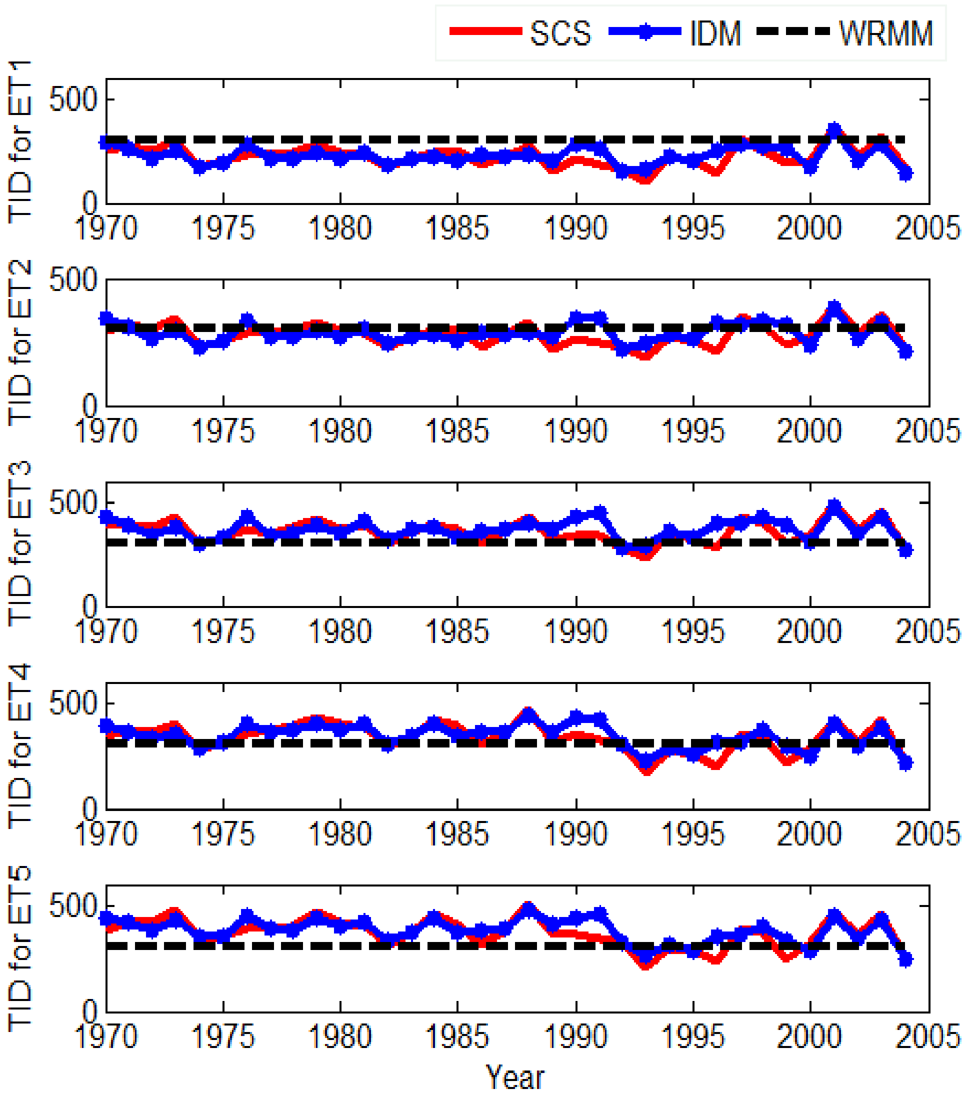

Figure 2-9 Total irrigation demand (mm) for combination of different ET_0 and irrigation models

The envelope of TID (MCM) in $SWAMP_{SK}$ was compared to licensed TID in WRMM in Figure 2-10. In order to explore the sensitivity of the water resource system to the selection of irrigation demand models, the SCS-ET1 and IDM-ET5 models were used as irrigation demand lower and upper boundaries in the analysis.

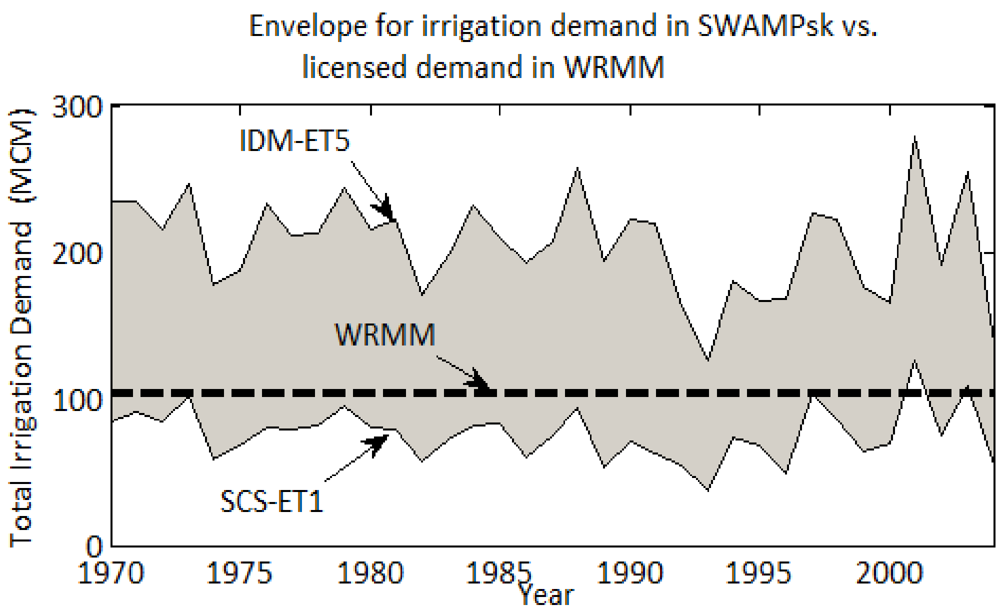

Figure 2-10 The envelope of irrigation demand in SWAMP$_{SK}$ based on alternative reference evapotranspiration and irrigation models versus constant (licensed) irrigation demand used in WRMM

Figure 2-11 shows the SWAMP$_{SK}$ and WRMM model results versus observed values for the period 1970-2004. Results for SCS-ET1 and IDM-ET5 for the SWAMP$_{SK}$ are shown in blue and red dots, respectively. The current irrigation demand is not large; therefore, the SWAMP$_{SK}$ is insensitive to irrigation model selection. The figure also implies that the SWAMP$_{SK}$ simulates the observed records as well as WRMM. It is not expected to have a perfect simulation of observed values as the water demand values within SWAMP$_{SK}$ and WRMM are based on licenses issued for the period 1970-2004.

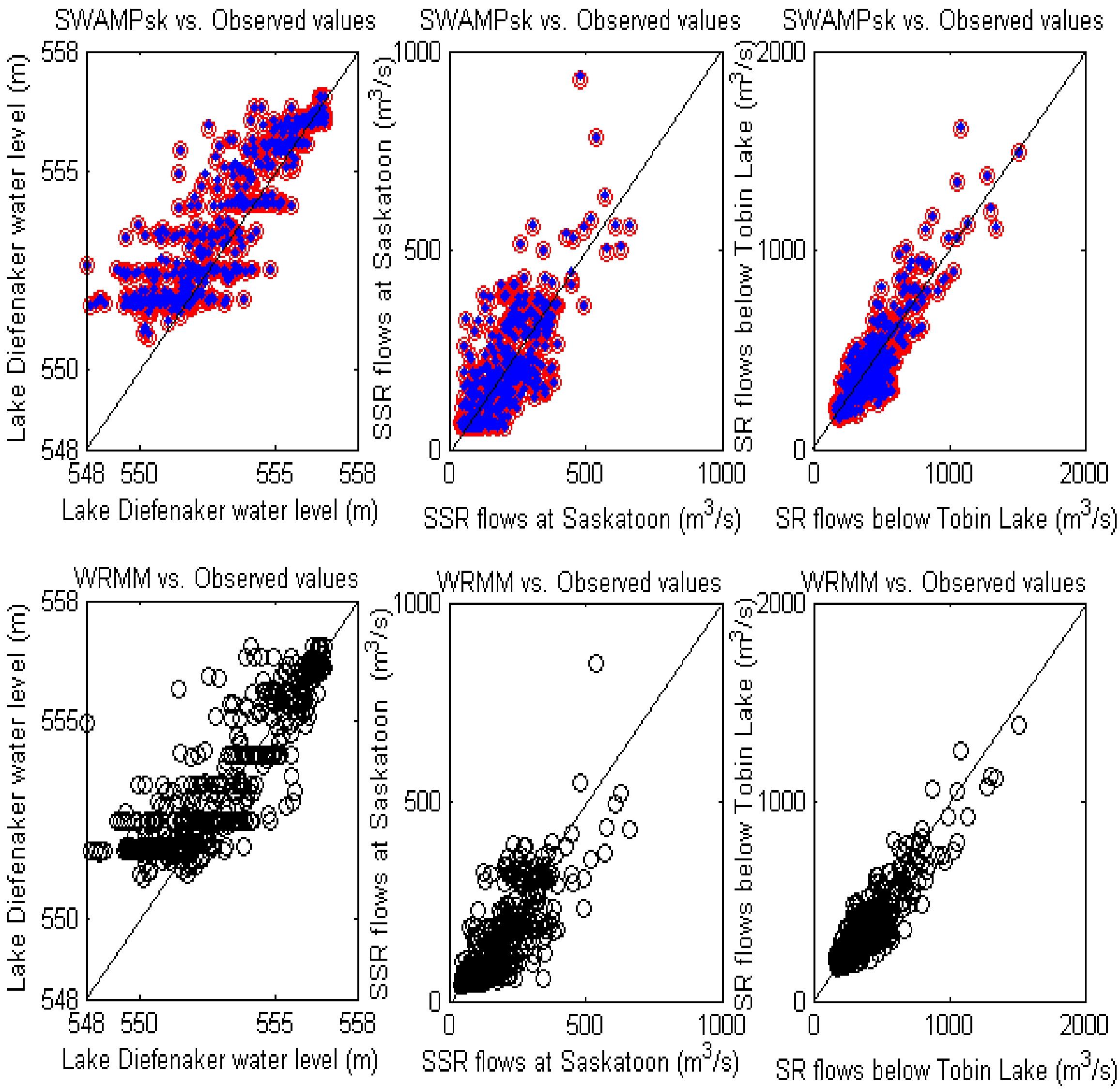

Figure 2-11 Comparison between the monthly SWAMP$_{SK}$ (Y-axis), WRMM (Y-axis) and the observed (X-axis) value for critical points in the system. Red and blue dots show the scatter plot between observed values versus SCS-ET1 and IDM-ET5, respectively

2.6 Application

To demonstrate the model capability, part of the $SWAMP_{SK}$ interface is shown in Figure 2-12. As an example of user-friendly capability, by increasing the irrigation area interactively, using a screen slider, the model visually shows the effect on flows at Saskatoon. $SWAMP_{SK}$ facilitates the exploration of strategic questions such as: is there adequate water available to support expansion of mining and agricultural production? How sensitive is the water resource system to changes in climate? What are the effects of different crop selections on Saskatchewan's economy and environment?

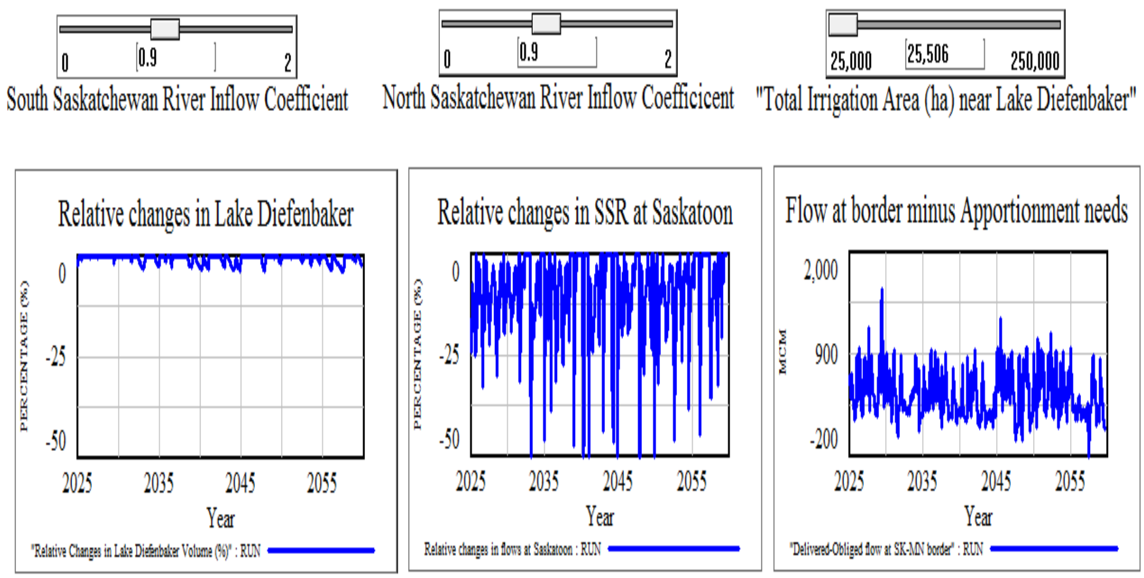

Figure 2-12 Parts of the $SWAMP_{SK}$ interface

"What-if" scenarios were generated for the current study to show the model capabilities in presenting the water policy issues of the future. Scenario (S0) is a base-case scenario; it includes the historical flows (1970-2004) with irrigation area of 40,000 hectares. Scenario (S1) simulates the system only when Alberta's outflows change due to climate change impact in Alberta. S1 represents the results for a 5% drop in flows for the North Saskatchewan River

(North Saskatchewan Watershed Alliance, 2008) and an 8.5% drop in flows for the South Saskatchewan River (Pomeroy et al., 2009) at the Alberta/Saskatchewan border, also with irrigation area of 40,000 hectares. Scenario (S2) is an agricultural expansion scenario with irrigation area of 200,000 hectares, whereas historical flows remain unchanged. Scenario (S3) is a combination of changes in Alberta's outflows and agricultural expansion scenario; it demonstrated the results for combination of flows in S1 and irrigation area in S2.

The IDM-ET5 and SCS-ET1 irrigation models were used with each of the four scenarios. Potash mining had higher priority than irrigation and hydropower sectors. In all configurations, no water shortage occurred for the mining sector, therefore, the economic value of water for this sector is not shown as it remained constant throughout the analysis.

NPV was calculated for a 35-year planning period at a discount rate of 5% for hydropower and irrigated agricultural sectors (Figure 2-13). This discount rate was chosen to compare our economic results with the ones presented in SIPA (2008). In addition, the considered simulation period represents a plausible window of 35 years and does not explicitly refer to a specific future time-series. The relative changes in the economic benefit of these two sectors are the main concern rather than the exact numbers generated by the model.

The climate-change induced drop in mean annual flow from Alberta will not affect the revenues of the irrigation sector with a constant 40,000-hectare area under production (S1). When the irrigation water demand is low at 40,000 hectares (S0), hydropower production is insensitive to the model selection for irrigation demand; however, as the irrigation area is increased (S2), the irrigation water demand increases in importance, and its magnitude affects the hydropower production. Comparison of S2 and S0 scenarios shows that the economic benefits to Saskatchewan grow when irrigation acreage is increased. The net benefit from agriculture is higher than the reduction in hydropower net benefit. This conclusion is consistent with the SIPA (2008) study on the economic aspects of irrigation expansion. The economic results for S3 show that the drop in apportioned flows will somewhat affect the economics of the expanded irrigation area, with benefits to hydropower reduced slightly.

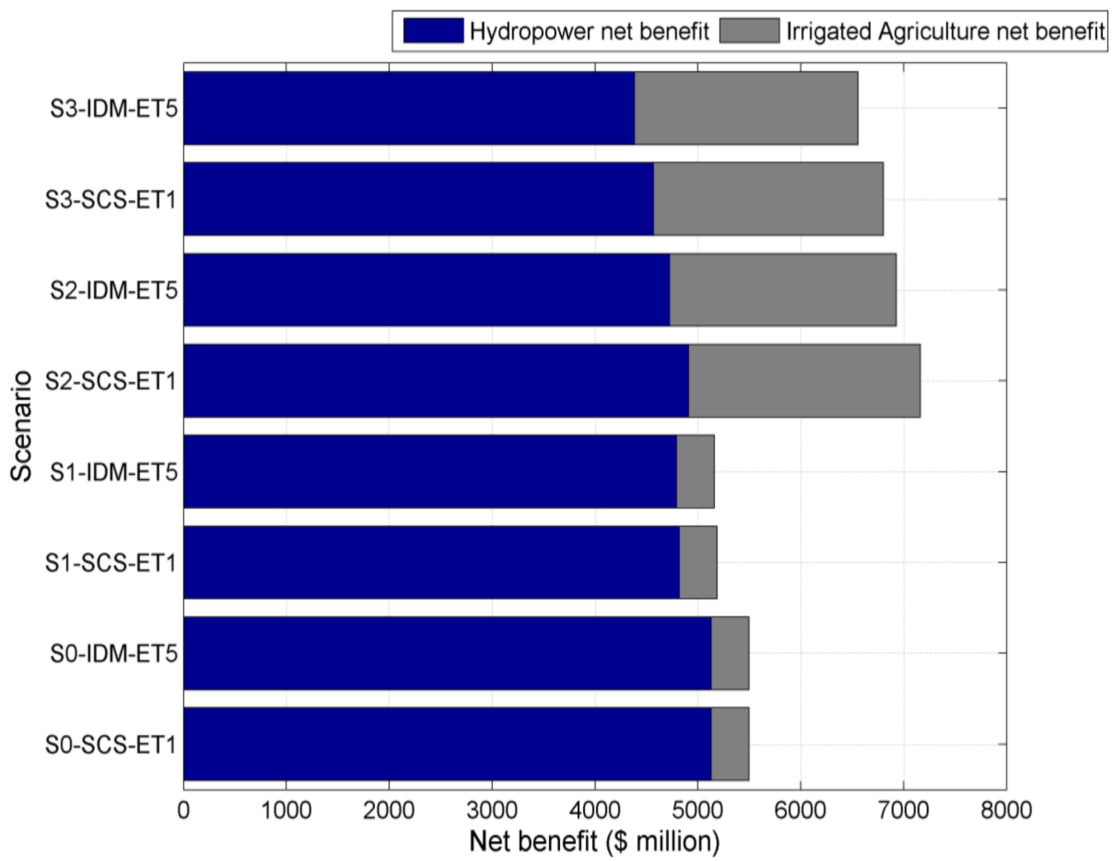

Figure 2-13 Economic evaluation of water for hydropower and irrigated agriculture

Simulation results in terms of lake levels and river flows for the various scenarios are presented in Figure 2-14. The water level in Lake Diefenbaker in May drops below 551 m if the irrigation area is increased as in S2. The water level would decrease further in S3 when agricultural expansion is matched with lower flows from climate change. Even in the base-case scenario (S0), Lake Diefenbaker fails to meet the July 1 requirement water levels in some years. As irrigation demand is at a maximum in July, significant decreases in water levels occur in the S2 and S3 scenarios. These July shortfalls in lake levels would present difficulties for recreational boating and pumping water for various uses such as irrigation.

Flows at Outlook under all scenarios are above the environmental flow requirement of 42.5 (m^3/s) to ensure dilution of Saskatoon's wastewater. The scenarios do, however, point to potential problems downstream in which it would not be possible under drought conditions for Saskatchewan to deliver the 50% of its natural flows and 50% of flows receives from Alberta to Manitoba, on monthly basis. The situation would become increasingly severe moving from S0 to S1, S2, and S3.

Figure 2-15 shows the relative monthly reduction of water level in Lake Diefenbaker, SSR at Saskatoon, and SR below Tobin Lake under three different scenarios. The drop in flow below Tobin Lake can be particularly problematic because it directly affects the environment and livelihoods of First Nation communities who live in the downstream Delta region. Comparison between relative reduction in monthly water flows under S1 and S2 scenarios at these critical points indicate that the system is more sensitive to the 400% irrigation expansion than to a mere 8.5 and 5.0 percent drop in mean annual inflows of the SSR and NSR at Alberta/Saskatchewan border. The monthly reduction in river flows at the points of concern becomes large in the S3 scenario (combination of reduction in system inflows and irrigation expansion).

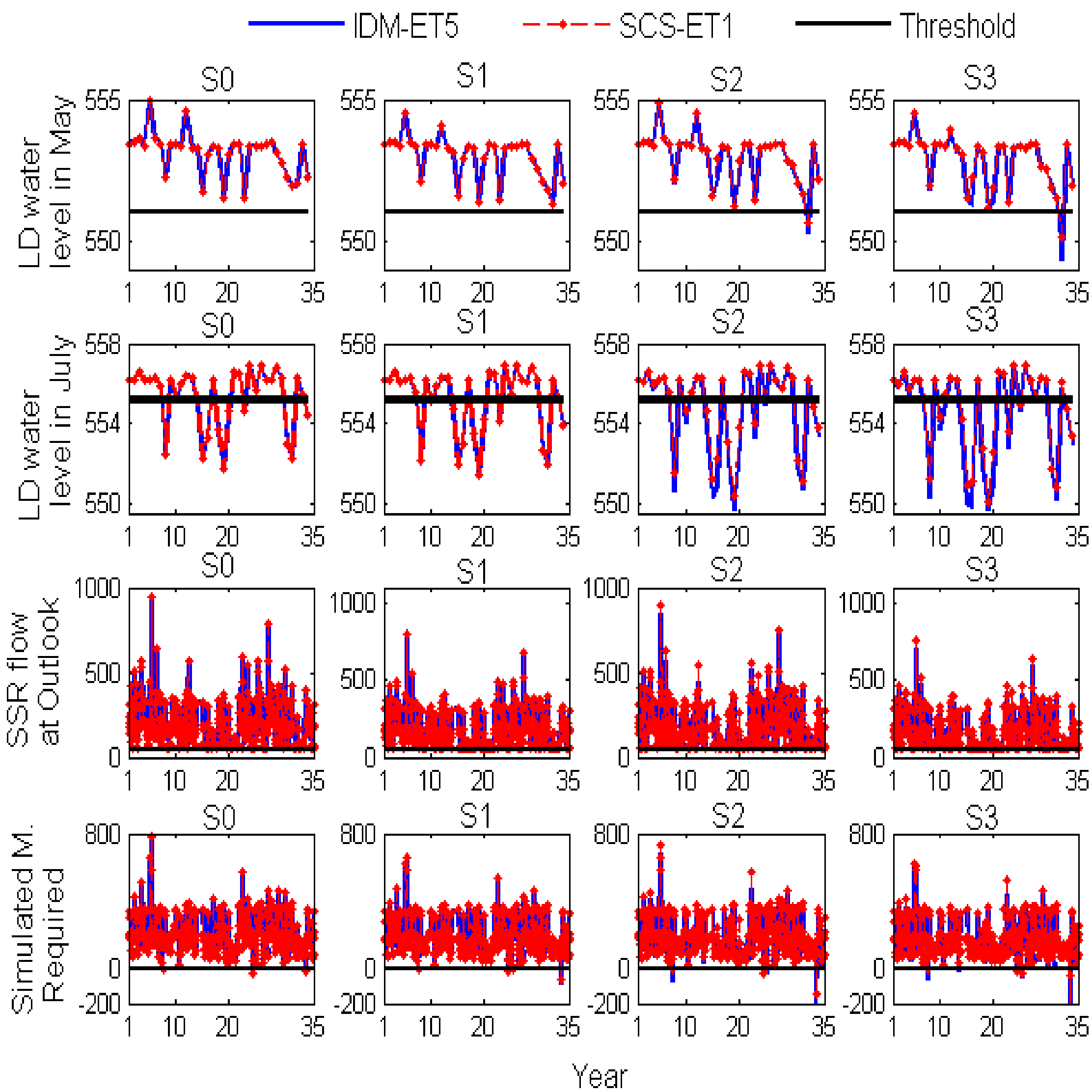

Figure 2-14 Results for Saskatchewan's target objectives: May and July water levels (m) for Lake Diefenbaker (LD), SSR at Outlook downstream of Lake Diefenbaker (m^3/s), and difference between simulated and the required SR flow delivery to Manitoba (m^3/s)

Simulation results for these preliminary scenarios are summarized in Table 2-5 and indicate that the 400% irrigation expansion proposed by the Ministry of Agriculture would provide direct economic benefits to Saskatchewan but lead to occasional failure to system criteria in some years. Under current operating rules, agricultural expansion would lead to reductions in reservoir water levels and river flows, especially during drought years under the climate change when Alberta's input to the system are reduced.

Future studies will explore: (1) the climate-related uncertainties and what they imply for future river flows (2) effects of climate change on irrigation demand with implications for various sectors and environmental flows; and (3) potential impacts of hedging strategies to allow increases in irrigated area only when other demand requirements are met.

Overall, $SWAMP_{SK}$ has high accuracy in simulating the water resources in Saskatchewan and the presented scenario analyses demonstrate the model's capability in representing water system behavior. However, this model has limitations: one is the coarse (monthly) time resolution of $SWAMP_{SK}$, which can be problematic for accurate estimation of irrigation demand. In addition, it is important to know the system's performance under extreme conditions (e.g. flooding) at fine time resolution. Future versions of this model will include a weekly time step to accurately present process in the system. Another limitation of this simulation-based model is that it does not include adaptive water allocation policies and the operational policies are applied offline and do not vary over time.

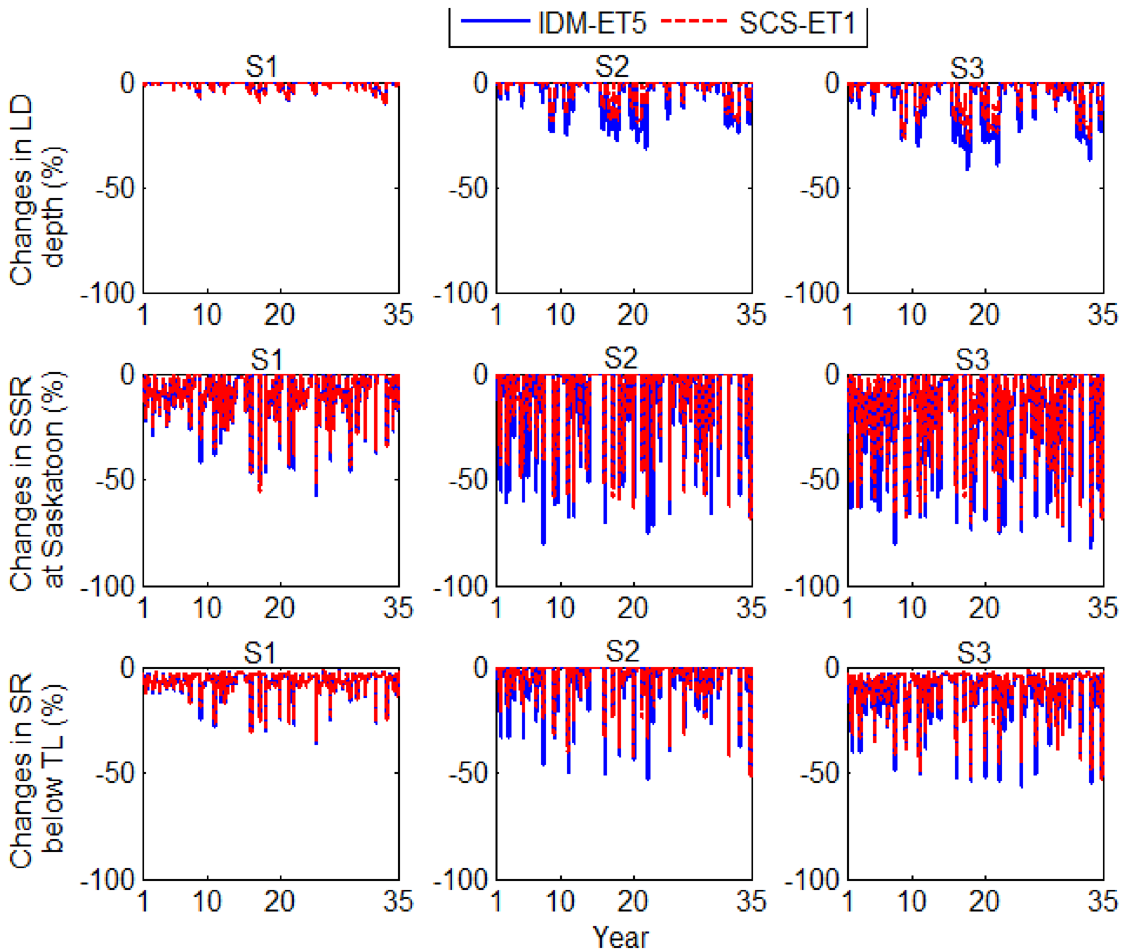

Figure 2-15 Changes in percentage for monthly Lake Diefenbaker (LD) depth, SSR river flow at Saskatoon and SR flow below Tobin Lake (TL) for S1, S2, and S3 scenarios using two irrigation models and reference evapotranspiration equations (SCS-ET1 and IDM-ET5; the lower and upper bound of irrigation demand envelope) relative to base scenario (S0), i.e. $(\frac{S1-S0}{S0})*100$, $(\frac{S2-S0}{S0})*100$, and $(\frac{S3-S0}{S0})*100$.

Table 2-5 Simulation scenario results for hydropower and agricultural economic benefit as well as Saskatchewan's environmental and inter-provincial concerns

Sector	Descriptions	S0	S1	S2	S3
Hydropower	Net revenue ($M)	5129	4807	4817	4476
Irrigated agriculture	Net revenue ($M)	370	370	2229	2205
Lake Diefenbaker level in May	Number of years lake level < 551	0	0	1	1
	Mean magnitude of difference (551-lake level) if lake level<551 (m)	0	0	0.75	1.64
Lake Diefenbaker level in July	Number of years lake level < 555	10	11	15	15
	Range of magnitude of difference (555 -lake level) if lake level<555	0.5-3.4	0.36-3.7	0.04-5.3	0.38-5.3
	Mean magnitude of difference (555-lake level) if lake level<555 (m)	1.87	2.1	2.69	3.13
Apportionment requirement (APR)	Number of months simulated flow toward Manitoba (SIM) <APR	2	3	3	3
	Range of magnitude of difference (APR-SIM) if SIM< APR on monthly scale (m^3/s)	10-20	3-78	18-229	11-294
	Mean magnitude of difference (APR-SIM) if SIM< APR on monthly scale (m^3/s)	15	31	89	117
Environmental flow requirement (42.5 m^3/s)	Number of months river flow<42.5 m^3/s	0	0	0	0
	Magnitude of difference (42.5-river flow) if flow<42.5 on monthly scale (m^3/s)	0	0	0	0

2.7 Conclusions

$SWAMP_{SK}$ integrates water resources and socio-economic aspects of water availability and demand. A detailed dynamic irrigation demand model was included to incorporate evapotranspiration, soil moisture, and irrigation efficiency into the water resource system. Results were sensitive to the choice of irrigation demand model and the way that they represent the system under increased irrigation area. Results also show that agricultural expansion would increase economic benefits to the Province with small reductions in hydropower capacity even when agricultural expansion is coupled with a warming climate scenario. This is because there is excess capacity in the system for all but the driest years. However, the combination of large agricultural expansion and warming climate scenario would reduce lake levels and river flows and could compromise recreational uses and downstream livelihoods.

$SWAMP_{SK}$ can be used to evaluate the Saskatchewan's water security concerns by considering the uncertainties associated with flows, irrigation demand estimation, potential infrastructure construction, and policy interventions. The proposed modeling approach here to estimate the irrigation demand and assess the irrigation demand uncertainty with respect to the reference evapotranspiration/soil moisture model selection is useful for water resources studies in the areas that agriculture is the key water use. The calibration method proposed here is also generic and can be potentially applicable across a wide range of water resource situations. More generally, the SD modelling framework provides a useful basis for stakeholder engagement in the modelling process and $SWAMP_{SK}$ is an important first step towards the provision of a user-focussed decision support system for water resources in Saskatchewan.

2.8 Acknowledgments

Financial support for this project was provided by the NSERC-DG, a Civil and Geological Engineering Departmental scholarship and the Global Institute for Water Security, University of Saskatchewan. The authors would like to thank Bart Oegema of the Saskatchewan Water Security Agency for providing the WRMM model for Saskatchewan, and helpful advice concerning current policy and operational management.

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Chapter 3 - Integrating Supply Uncertainties from Stochastic Modeling into Integrated Water Resource Management: Case Study of the Saskatchewan River Basin

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Contribution of the PhD candidate

The PhD candidate used the streamflow reconstruction approach proposed in Nazemi et al. (2013) to assess the performance of SaskRB-Saskatchewan under changing conditions. To avoid reproducing the reconstruction method, Dr. Nazemi provided stochastic streamflow realizations and the candidate carried out the computer program development and simulation of the system under changing conditions. Moreover, the candidate rigorously evaluated the strength and weakness of methodology developed by Nazemi et al. (2013). The co-authors provided advice on various aspects of the study. The candidate created the manuscript with all co-authors providing critical review and editing of the manuscript.

Contribution of this chapter to the overall study

This work aimed at assessing the performance of the water resource system in the SaskRB-Saskatchewan under changing water availability and irrigation expansion. The stochastic streamflow realizations and scenarios of gradual increase in irrigation area were fed into the developed $SWAMP_{SK}$, presented in Chapter 2. This work presents visualization of the system vulnerability in the form of hydro-economic trade-offs among competing sectors under the considered scenarios of change. This work provides an example of the utility of the model developed in chapter 2. The reconstructed flow realizations and computing platform built for the computational activities in this chapter are also used in Chapter 4.

3.1 Abstract

A warming climate and land management intensification have altered water availability characteristics in many regions of the world. Incorporation of water availability uncertainties into long-term water resources planning and management is, therefore, significant from both a scientific and societal perspective. This study proposes a set of analyses for integrated water resource management under changing water availability and demand expansion, based on a newly developed methodology for vulnerability assessment. The basin of interest for the proposed analysis is the inter-provincial Saskatchewan River Basin (SaskRB) in Canada, which supports a wide range of water demands, from municipal and industrial use to irrigated agriculture and hydropower. Proposals for an increase in irrigated area are used as a context for exploring the joint effects of current and future water availability uncertainty and increasing irrigation demand conditions on the water resource system. Changing water availability conditions are represented by perturbing annual volumes and the seasonal timing of the hydrograph peak as input to an integrated water resources model. The analysis enables evaluation of the effects of economic development plans as well as variations in volume and peak timing of flows on water availability and economic productivity, including possibilities for failure to meet demands. Results for the SaskRB show that a large increase in irrigated agriculture raises average net revenues, but these are highly dependent on water availability conditions and loss of revenue may arise under drought conditions. Hydropower production is more sensitive to changes in annual inflow volume than to changes in either annual timing of the peak flow or the magnitude of irrigation expansion. Irrigation expansion can considerably affect the peak flows in the Saskatchewan River Delta, the largest inland delta in North America, during low flow conditions.

For example, a 400% increase in irrigated area under a 25% decrease in inflow volume and four week earlier annual peak timing, can reduce the frequency of peak flows in the Delta by more than 50 percent, though potential effects on the riparian and aquatic ecosystems remain uncertain. This case study illustrates the practical utility of stochastic analysis of system vulnerability to feasible futures in such a way that socio-economic trade-offs can be readily visualized and understood. Such performance assessments are useful for long-term water resources planning and management under uncertain water availability.

3.2 Introduction

Water resource management will play a key role in allocating limited freshwater under increasing demands and uncertain supplies. Although historical data have been used for long-term water resources planning, Milly et al. (2008) have questioned whether these records provide an accurate picture of future climate and hydrological conditions. They defined stationarity as the envelope of variability surrounding historical hydrological characteristics (e.g., annual streamflow volume, and timing of the peak) and argued that climate change and human manipulation of natural water systems (see also Nazemi and Wheater, 2015a, b) have undermined the assumption of stationarity. The probability density functions associated with historical flows are no longer an accurate basis on which to make current and future water resource decisions (Milly et al. 2008; Reed et al., 2009). The implications of non-stationarity for water resource management have been extensively discussed (e.g., Barsugli et al., 2012; Salas et al., 2012; Garrick and Hall, 2014; Borgomeo et al., 2014; Steinschneider et al., 2015).

A variety of models have been used to estimate future streamflow conditions, but results depend upon the climate model selection, emission scenarios, downscaling methods, and choice of hydrological models (Fowler et al., 2007; Wiley and Palmer, 2008; Wilby, 2010; Beven, 2011; Pielke and Wilby, 2012; Sing et al., 2014; Cai et al., 2015). Given the high level of uncertainty associated with such climate model results, various studies have recommended incorporating non-stationarity in water resources practices without direct use of climate models (e.g., Wilby and Dessai 2010; Prudhomme et al., 2010; Brown and Wilby, 2012; Pielke et al., 2012; Steinschneider and Brown, 2012; Steinschneider and Brown, 2013). Herman et al. (2015) presented an insightful classification for this bottom-up framework (from the needs of stakeholders to regional vulnerability assessment) and categorized the methods into Robust Decision Making (Lempert, 2006), Decision Scaling (Brown et al., 2011), Info-Gap Analysis (Ben-Haim 2006), and Many-Objective Robust Decision Making (Kasprzyk et al., 2013). Although these approaches avoid direct use of Global Climate Models (GCMs), with their associated uncertainties, hydrological modeling uncertainties are still embedded in the associated decision analysis (Wheater and Gober, 2013; Nazemi and Wheater 2014a). In fact, uncertainties in hydrological models may be equal to or greater than those associated with climate models (Steinschneider and Brown, 2014). Such limitations have led to schemes that assess system vulnerability without applying hydrological models. Nazemi et al. (2013) proposed a methodology for risk assessment and sensitivity analysis based on stochastic synthetic flow series corresponding to feasible changes in long-term flow characteristics, and using the generated synthetic streamflow envelope for water resource vulnerability analysis.

This case study is targeted to apply the new methodology for vulnerability analysis of a water resource system, proposed by Nazemi et al. (2013), and to extend the method to analyze the changing demand in conjunction with changing water availability conditions. The vulnerability analysis is implemented on the inter-provincial Saskatchewan River Basin (SaskRB), and in particular, on the water resource system in the western Canadian province of Saskatchewan. Incoming flows from the upstream province of Alberta are the dominant source of water availability in Saskatchewan. There are two major challenges associated with water resource management in Saskatchewan. First, a warming climate has already altered the streamflow characteristics in Alberta (e.g., Pomeroy et al., 2009) and these determine Saskatchewan's water availability. Second, there are plans in Saskatchewan to increase current areas of irrigated agriculture by 400% in the near future, although different possibilities for expanding agriculture are still under review (Saskatchewan Irrigation Projects Association, 2008). One important scientific and policy question is the extent to which changing water availability and development conditions can affect this water resource system.

The purpose of this case study is to present sets of analyses to assess the vulnerability of the water resource system in Saskatchewan to changing water availability conditions and varying levels of agricultural expansion. First inflows at Alberta/Saskatchewan (AB/SK) border were reconstructed using Nazemi et al. (2013). Second, further validation results for this stochastic reconstruction scheme are provided to ensure inflows are sufficiently describing changing water availability conditions. While earlier validation results (Nazemi et al., 2013) only focused on the preservation of the long-term flow characteristics and temporal dependence structures within the reconstructed series, here the authors further inspected how synthetic series can preserve historical weekly flow duration curves, inter-annual characteristics and spatial dependence. Third, the ensemble of reconstructed flows, along with scenarios of irrigation expansion, were input to an integrated water resource management model, developed by Hassanzadeh et al. (2014) for Saskatchewan. The simulation results in this case study were then used to reflect the potential socio-economic vulnerabilities in multiple water sectors and inform policy makers about the possible trade-offs in the system.

The Case Study Section briefly explains the SaskRB in Saskatchewan. The water resource model, the stochastic reconstruction methodology, and the design of the simulation experiment are presented in the Methods and Materials Section. The validation of the reconstruction scheme and socio-economic vulnerability maps, and sensitivity analyses are presented in the Results Section. Finally, the Discussion and Conclusions Section summarizes results, and points to the larger scientific, modeling, and policy issues revealed by the case study.

3.3 Case Study

A simple schematic of the Saskatchewan River Basin (SaskRB) in the province of Saskatchewan, Canada is presented in Figure 3-1 with squares representing reservoirs, arrows showing channel flows, main river channels shown with thick arrows, and key water diversions shown with thin arrows. The 1969 Master Agreement on Apportionment approved by Canada’s three western Prairie Provinces (Alberta, Saskatchewan, and Manitoba) requires Alberta to pass half of the natural flows of the Saskatchewan River to Saskatchewan. Saskatchewan, in turn, is also required to pass half of that flow and other natural flows in Saskatchewan to Manitoba

(Prairie Province Water Board, 2015). About 80% of the water availability in Saskatchewan is provided by the North Saskatchewan and the South Saskatchewan Rivers (NSR and SSR). Only 20% of water availability is supported by local flows in the province. The NSR and SSR rivers have drainage areas of 122,800 and 146,100 km^2 within both provinces of Alberta and Saskatchewan and have mean annual discharges of 213 and 215 m^3/s at the AB/SK border, respectively. The SSR flow in Saskatchewan flows to Lake Diefenbaker, which, with a volume of about 9400×10^6 m^3, is a multipurpose reservoir that supports water supply, flood protection, and environmental flows. It delivers water to two sub-systems, as well as to irrigated agriculture, hydropower facilities, and downstream flow requirements (Pomeroy et al., 2005). The current irrigation area in the Saskatchewan water resource system is about 24,100 ha (SWSA, 2015). Based on current operational policies, the minimum environmental flow requirement of the SSR flow downstream of Lake Diefenbaker is 42.5 m^3/s and is regulated through releases from the lake's Coteau Creek hydropower station. The regulated SSR flow downstream of Lake Diefenbaker supports several communities and cities, including the City of Saskatoon. The SSR flow downstream of Saskatoon joins the NSR to form the Saskatchewan River (SR). The SR passes through two hydropower plants and further feeds the Saskatchewan River Delta (SRD), which is a home for diverse animal population, birds, and fish species including endangered species such as Lake Sturgeon (Committee on the Status of Endangered Wildlife in Canada, 2015). Such environmental diversity has high cultural, economic, and social value for aboriginal people, First Nations, whose livelihood depends on fishing, hunting and trapping (Partners for Saskatchewan River Basin, 2015). Although frequency of peak SR flows are highly important for replenishing the SRD ecosystem, extreme floods in the SRD can cause physical damage to the aboriginal communities and threaten their security. The SR finally flows to Manitoba.

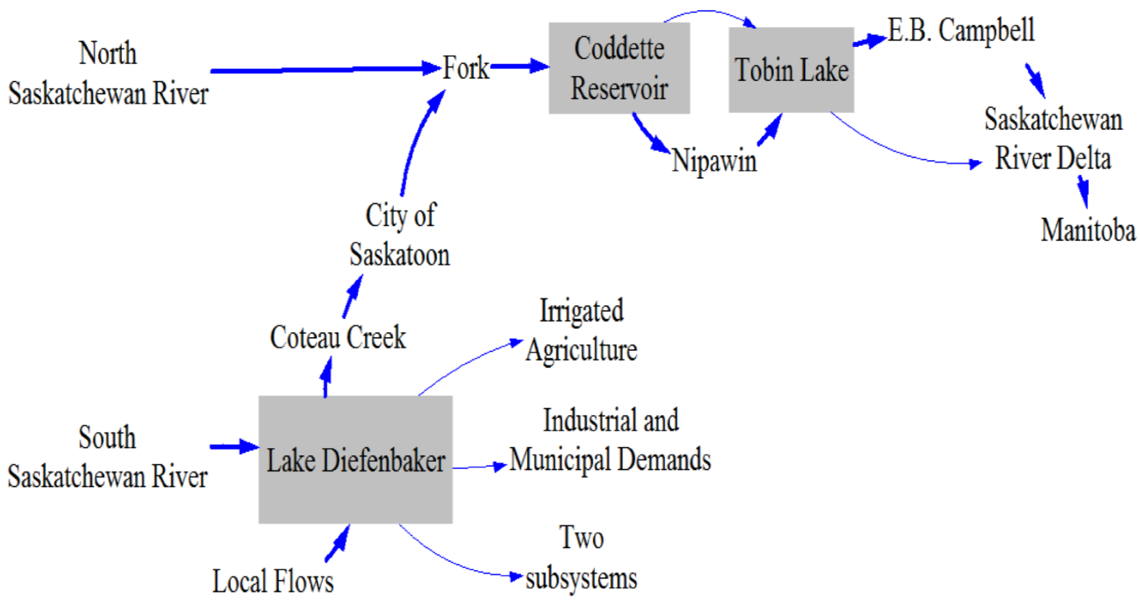

Figure 3-1 A simple schematic of the water resource system in Saskatchewan River Basin in Saskatchewan, Canada including main flows, reservoirs, and water demands.

In the Canadian Prairies, the key hydrological features of water availability can be quantified by two generic annual streamflow characteristics, i.e. the annual streamflow volume and timing of the annual peak (Nazemi et al., 2013). Changes in these streamflow characteristics, beyond operationally resilient thresholds, can cause various forms of vulnerability in the water resource system (Nazemi and Wheater, 2014b). Winter warming and changes in the pattern of snowmelt and glacial melt as well as human activities in Alberta are likely to affect annual volume and timing of the SSR and NSR flow regimes at the AB/SK border (e.g., Lapp et al., 2009; Shepherd et al., 2010). For instance, Pomeroy et al. (2009) projected changes in the annual SSR volume in the range of -22% to 8%. They also found that projected increases in temperature in the region will cause shorter and warmer winters in Saskatchewan, thus affecting the timing of prairie spring snowmelt and summer rainfalls. For the NSR, the North Saskatchewan Watershed Alliance (2008) estimated a range of -23% to 15% changes in the annual flow volume. These uncertainties associated with NSR and SSR water availability conditions pose significant challenges for long-term economic and water planning in Saskatchewan.

Expanding irrigated area should be considered with caution as currently irrigation demand is the largest consumptive water use in Saskatchewan (Martz et al., 2007). Under changing water availability and expanding irrigation area, water shortage for urban and industrial demands is not a challenging issue because these needs have high priority in the water resource system. In an average year, consumptive water use represents only 20% of annual flow, and the needs of cities and industry are easily met. Although this system might have enough water to meet consumptive demands on average, concerns are more related to changes in the SRD flow regime, trade-offs between irrigation and non-consumptive hydropower, and system response to drought and flood conditions.

3.4 Methods and Materials

The main objective of this study is to assess the SaskRB system vulnerability under changing water availability and economic development conditions. To implement this, three steps were followed. First, a feasible range of possible changes in water availability conditions was estimated based on geographic characteristics of the basin, results of available climate model projections, and potential impacts of human activities on water availability variation in the region. Second, large ensembles of flows were stochastically generated to correspond to the selected changes in streamflow regime. Third, the generated flows were combined with economic development plans and were fed into an integrated water resources model ($SWAMP_{SK}$) developed for the basin.

3.4.1 $SWAMP_{SK}$

$SWAMP_{SK}$ is an integrated water resources model developed by Hassanzadeh et al. (2014) for the SaskRB in Saskatchewan. This simulation model is constructed using the System Dynamics approach (Forrester, 1961), which has been extensively used in water resources modeling and management (e.g., Ahmad and Simonovic, 2002; Elshorbagy et al., 2005; Hjorth and Bagheri, 2006; Langsdale et al., 2007; Madani and Mariño, 2009; Ahmad and Prashar, 2010; Madani 2010; Simonovic, 2009; Davies and Simonovic, 2011; Hassanzadeh et al., 2012; Gohari et al., 2013; Wu et al., 2013; Gohari et al., 2014; Teegavarapu and Simonovic, 2014; Li et al., 2015; Sahin et al., 2015). The application of System Dynamics approach in water resources research has been reviewed by recent studies (e.g., Winz et al., 2009; Mirchi et al., 2012; Chen and Wei, 2014). $SWAMP_{SK}$ includes dynamic irrigation demand calculation and economic evaluation schemes. The soil-moisture model in the $SWAMP_{SK}$ estimates irrigation water demand for the main crops in Saskatchewan considering climate and antecedent soil moisture conditions. The economic value of water in key water sectors, including irrigation, and hydropower is calculated by considering the amount of water consumed for unit productions of crops, and electricity as well as the total cost and revenue of this production. The simulation accuracy of the model was verified in Hassanzadeh et al. (2014) by comparing the simulation results of the water allocation component of $SWAMP_{SK}$ with the existing operational model and observed records. The temporal resolution of the $SWAMP_{SK}$ is weekly and covers the period of 1980-2010.

3.4.2 Stochastic reconstruction of streamflow

Nazemi et al. (2013) provided a stochastic scheme to systematically produce weekly streamflow realizations under predefined changes in the annual streamflow volume and peak timing. In brief, this method uses the empirical distributions of historical weekly flows, perturbs them in two stages under some simple assumptions and uses the perturbed weekly empirical distributions to generate new streamflow realizations with predefined shifts in the mean annual flow and the timing of the peak. First, a set of observed annual streamflow series with weekly resolution, along with desired shifts in the flow volume (a multiplicative change factor) and timing of the annual peak (an additive change factor) should be provided to the algorithm. Then, the additive change factor should be applied to each annual streamflow series based on a simple assumption, resulting to a shifted annual hydrograph. The shifted annual flow hydrographs together provide a new set of intermediate empirical distributions for weekly flows. This new set of empirical distributions is further perturbed using the multiplicative change factor using quantile mapping. This results in a set of perturbed weekly empirical distributions that can generate random streamflow realizations that are expected to have the desired shifts in the annual streamflow volume and peak timing, while preserving the temporal autocorrelation of the weekly flows. The random sampling procedure is based on the copula methodology (Nazemi and Elshorbagy, 2012). The Gaussian copula was adopted to maintain the temporal dependence structure within the generated annual streamflow hydrographs. This process can be repeated with multiple sets of shifts in the annual streamflow volume and timing of the peak to provide streamflow realizations with a wide range of streamflow properties.

3.4.3 Design of the simulation experiment

To evaluate the performance of the water resource system in Saskatchewan under uncertain water availability conditions, both NSR and SSR flows were reconstructed at the AB/SK border. The selected flow domain for producing these inflows corresponds to a range of -25% to 25% change in annual flow volume and -5 to 8 week change in timing of the annual hydrograph peak. This covers the feasible range of recent climate model projections presented in literature for annual streamflow volume inflows under increasing concentration of greenhouse gases (e.g., Pomeroy et al., 2009). The prescribed shifts in annual volume and peak flow timing can be considered to represent both seasonality of water demands and impacts of water resource management in Alberta (e.g., Nazemi et al., 2013).

It was noted that the spatial dependence between the NSR and SSR flows is relevant for flow reconstruction. Figure 3-2 represents the *p*-values, corresponding to the significance of spatial correlations between the weekly historical SSR and NSR flows. The analysis shows that weekly NSR and SSR flows are significantly correlated ($p < 0.05$) except for weeks between December and April (winter low flow conditions), hence such correlation must be represented for viable streamflow reconstruction. To jointly reconstruct the SSR and NSR flows, first, weekly SSR flows were generated using prescribed shifts in the historical timing and streamflow volume. For those weeks with significant correlation, the weekly NSR flows were reconstructed based on the synthetic SSR flows in the same week using linear regression. The weekly linear regression models were parameterized using the observed weekly flows in the SSR as the predictor and the observed weekly flows in the NSR as the predictand.

Changes in annual volume of flows and timing of the annual peak were used, i.e., gridding the flow domain using 5% and 1 week steps, respectively. Thus, 154 cells (11×14 combinations for changes in annual flow volume and peak timing) were considered. For each cell, 200 realizations of the 31-year streamflow time series (1980-2010) of weekly flows were generated and in total 30,800 (200×154) flow realizations for the simulation period were reconstructed. An *(x, y)* pair, defined as a cell, describes 200 realizations that have different streamflow time series but share specific streamflow characteristics of changes in the timing of the annual peak (*x*) in weeks and relative annual volume (*y*). Thus, 200 reconstructed flow realizations with historical annual peak timing and volume were labeled (0, 0).

To investigate the feasibility of irrigation expansion, the impact of uncertain water availability on water availability was evaluated under current and alternative irrigation development levels. In brief, S0 simulates the SaskRB under current irrigation demand and the changing water availability conditions described above. Scenarios S1, S2, S3, and S4 simulate the system under combinations of uncertain water availability conditions and 100%, 200%, 300%, and 400% increases in irrigated area, respectively. Tradeoffs between the benefits of these irrigation plans and potential impacts on other water uses are highlighted. The simulation period is assumed to be a span of 31 years and does not explicitly reflect a specific time period in future.

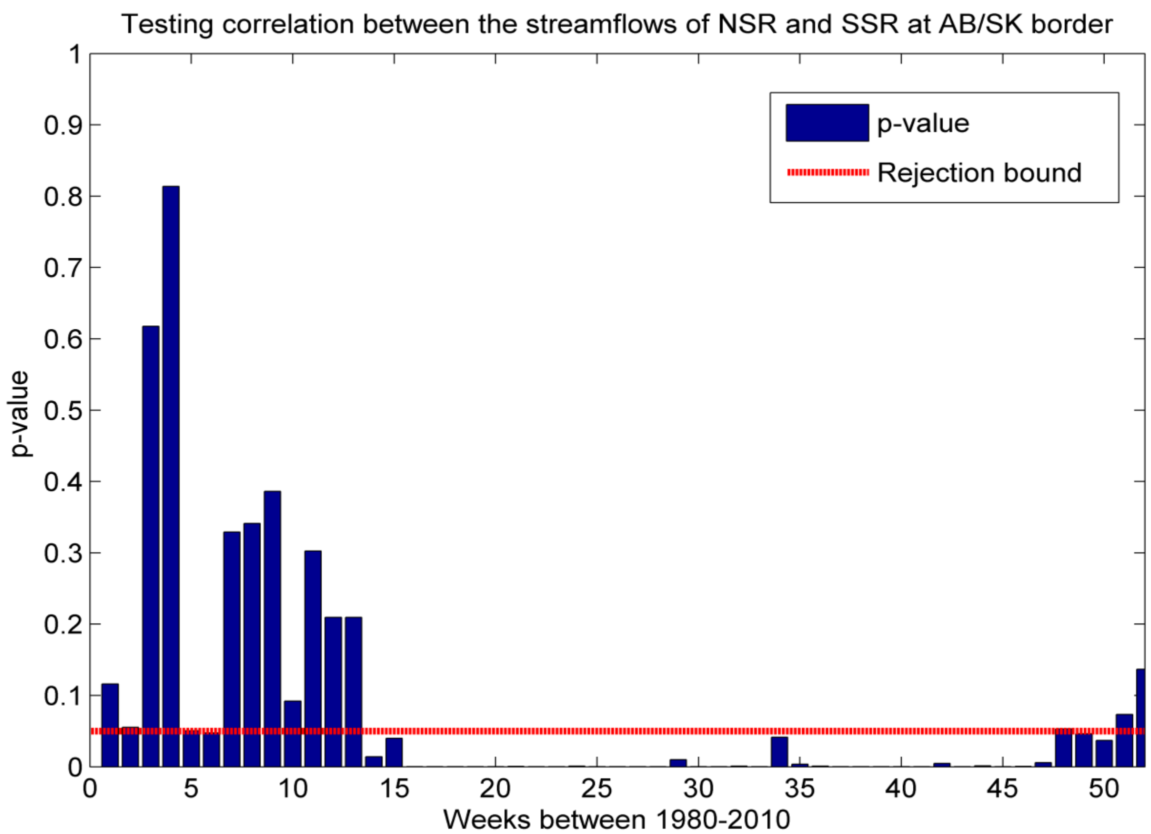

Figure 3-2 Testing the spatial correlation between weekly streamflows of NSR and SSR at the AB/SK border for the period 1980-2010.

3.5 Results

3.5.1 Testing the reconstructed flows at AB/SK border

Figure 3-3 shows an ensemble of long-term annual hydrographs (averaged over 31 years) reconstructed for the SSR at the AB/SK border, considering the predefined ranges for the shifts in the annual volume and timing of the annual peak. The dark area shows the entire ensemble; the light area highlights the reconstructed ensemble with no shifts in the historical flow regime

(0, 0). The dashed line shows the expected (averaged across 200 realizations) long-term hydrograph of realizations in the cell (0, 0), which fits the long-term historical hydrograph (solid line) quite well. The expected long-term hydrographs for the cells of (-4, -10%), (4, 10%), (-2, 20%), and (2, -20%) are also shown in the figure – see Appendix C, Section C.1 for additional test results for SSR and NSR.

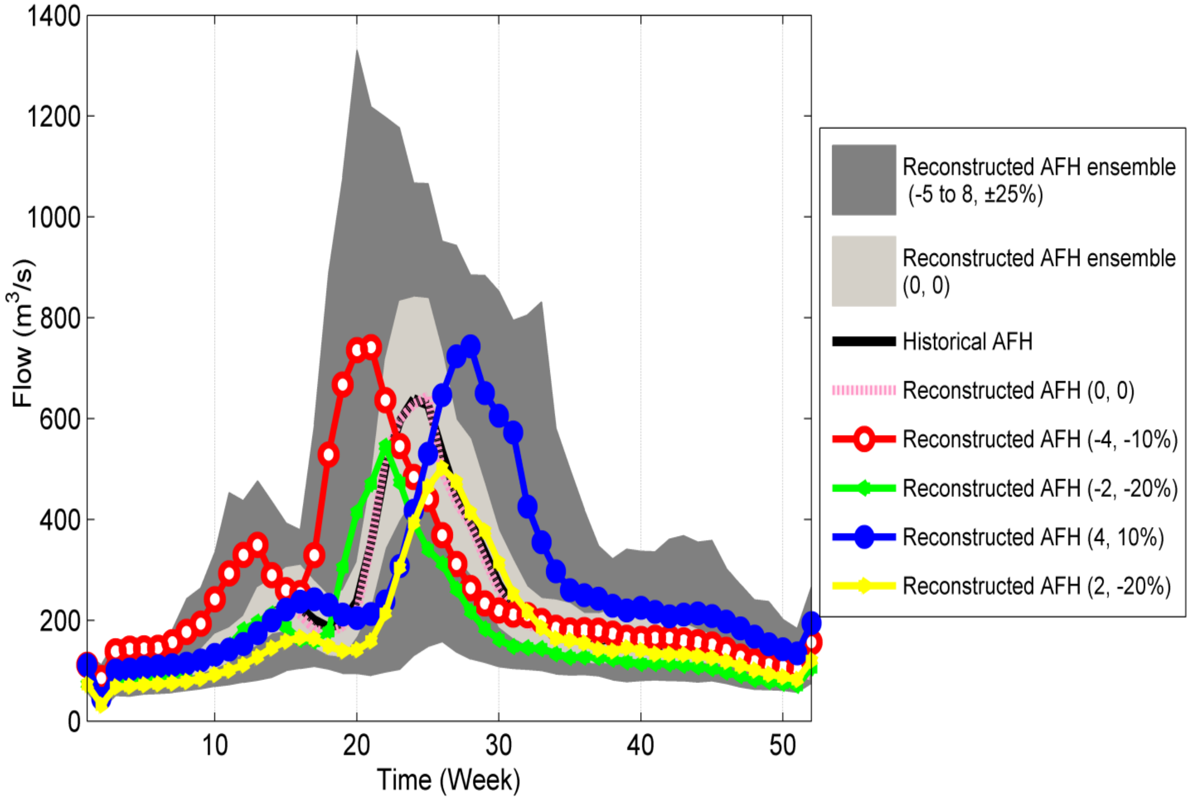

Figure 3-3 Annual expected flow hydrographs (AFH) for SSR at the AB/SK border.

Figure 3-4 shows the weekly flow-duration curves for observed flows versus 200 reconstructed flow realizations under cell (0, 0). The flow-duration curves represent the magnitude of weekly flows and the percentage of time when they are exceeded within the simulation period. For the SSR, the envelope of reconstructed flows successfully includes the observed flows. For the NSR, the reconstructed envelope of flows presents smaller values in the upper and lower tails and larger values in the rest of the flow-duration curve than the historical NSR flow quantiles. However, in general the reconstructed envelope of flows sufficiently covers the observed record.

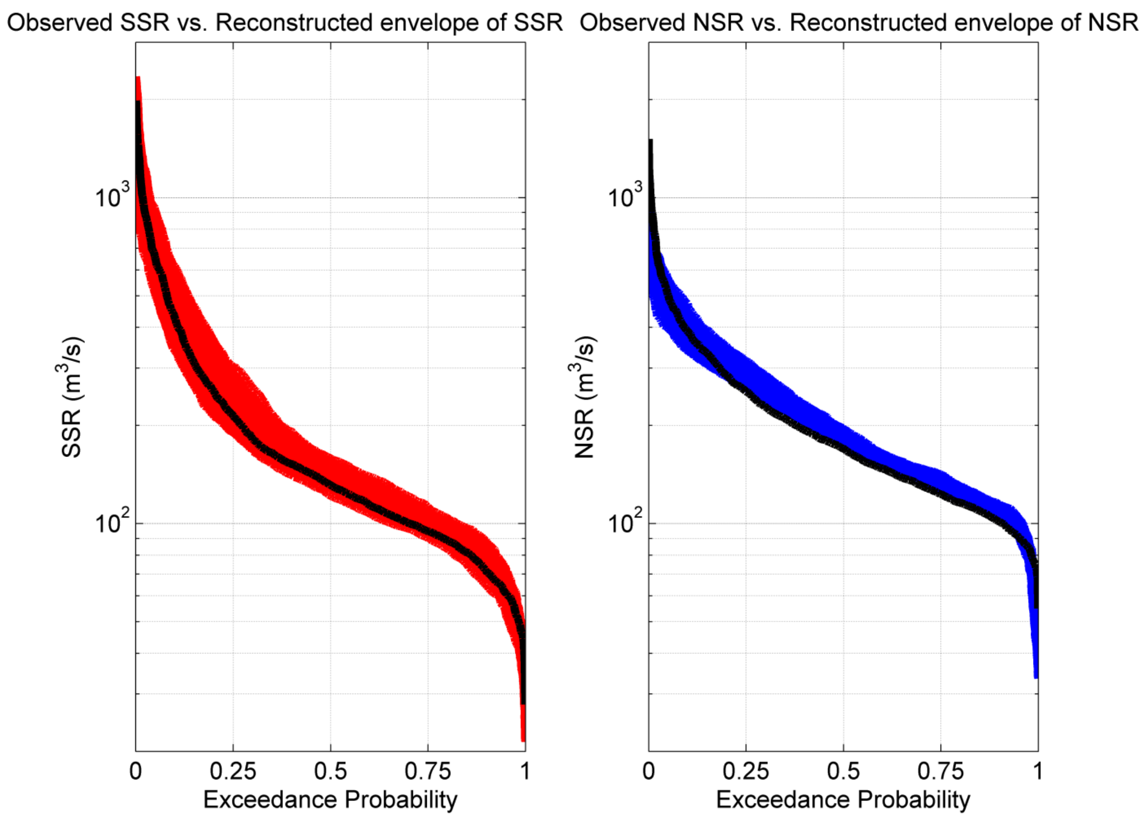

Figure 3-4 Flow-duration curves for observed flows (solid line) versus the reconstructed envelope of SSR and NSR flows.

Inspecting the inter-annual properties of the reconstructed flows, particularly drought sequences, provides further insight into the resemblance between the reconstructed and observed flows. Here, a dry year is defined as a year in which the mean annual flow is less than the long-term annual mean. Figure 3-5 shows the histogram of dry runs estimated from the observed SSR record and the corresponding reconstructed realizations under the (0, 0) conditions within the 31 years of simulation. Drought sequences in all realizations are found, averaged, and presented in Figure 3-5. The reconstructed realizations represent a similar range of dry year occurrences compared to the observed drought sequences.

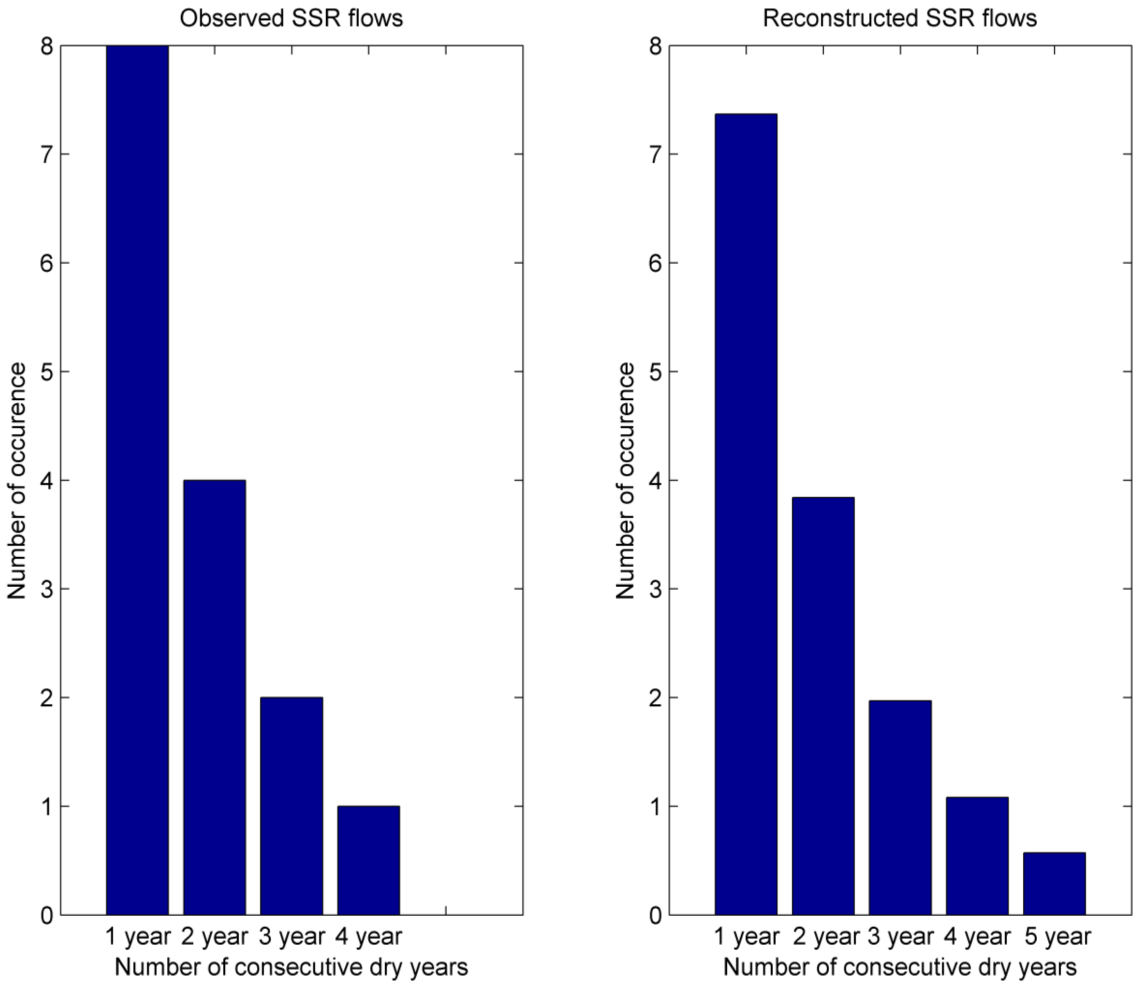

Figure 3-5 Comparison between sequences of dry runs in observed and reconstructed SSR flows.

The homogeneity of the synthetic NSR streamflow realizations that were obtained by linear regression and based on reconstructed SSR flows was also inspected. Ideally, synthetic NSR flows that are reconstructed independently or estimated based on reconstructed SSR flows should keep similar temporal structure as the observed NSR flows. Each panel in Figure 3-6 shows the weekly correlation matrix for the observed NSR flows (left), reconstructed NSR flows stochastically and independently (middle), as well as estimated NSR flows based on reconstructed SSR flows (right). Figure 3-6 shows that regardless of some differences, the main features of temporal structures within the observed flows are preserved in both independently generated and linearly estimated NSR flows based on SSR flows. As a result of these several analyses, it is concluded that generated ensembles of synthetic flows for the NSR and SSR can be used to explore the performance of the water resource system under changing water availability.

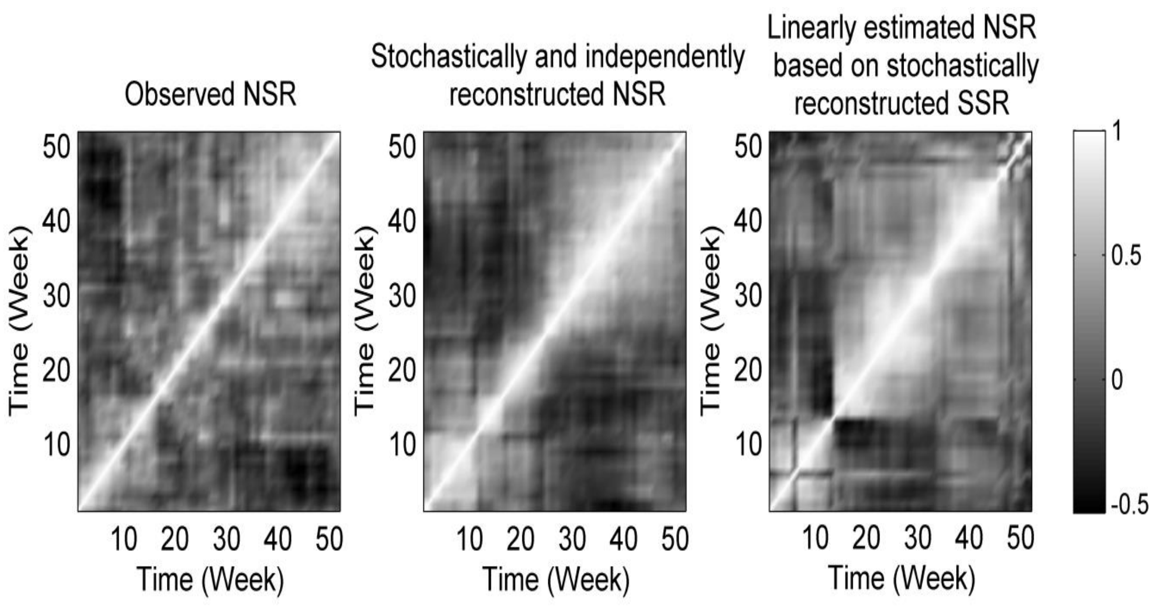

Figure 3-6 Temporal correlation matrices for observed NSR flows (left) as well as stochastically reconstructed NSR flows (middle) and linearly estimated NSR flows based on SSR (right).

3.5.2 Effects on municipal uses

The results of sensitivity analysis showed that the municipal sector was not vulnerable to changes in water availability, nor to the considered development conditions, because they have high priority in the current operational scheme. The current environmental flow requirement is relatively low (42.5 m^3/s) and can be supported under different scenarios and current operational policy.

3.5.3 Effects on Saskatchewan's apportionment commitment

According to the inter-provincial agreement, Saskatchewan must deliver 50% of incoming and local flows to the province of Manitoba through SR flow. The apportioned flow in percentage is defined as the amount of annual SR flow that moves downstream towards the Province of Manitoba over the sum of annual local flows and annual inflows coming from Alberta. The apportioned flow (%) must be equal to or more than 50%. To investigate the capability of meeting this commitment, the minimum apportioned flow based on the reconstructed realizations of SR flows was analyzed. First, for each realization the lowest apportioned flow during the simulation period of 31 years was computed. Then, the smallest amount for apportioned flow over the 200 realizations in each cell was extracted to present the lowest apportioned flow for that cell. Since there are 154 cells in the assessments (see the section for the Design of the simulation experiment), in total 154 lowest apportioned flow values for each scenario of irrigation development were obtained and the corresponding non-exceedance probability was calculated. The results for different development scenarios are shown in Figure 3-7. The zero non-exceedance probability and corresponding apportioned flows indicate that under all development scenarios, Saskatchewan can at least apportion more than 50% of water downstream.

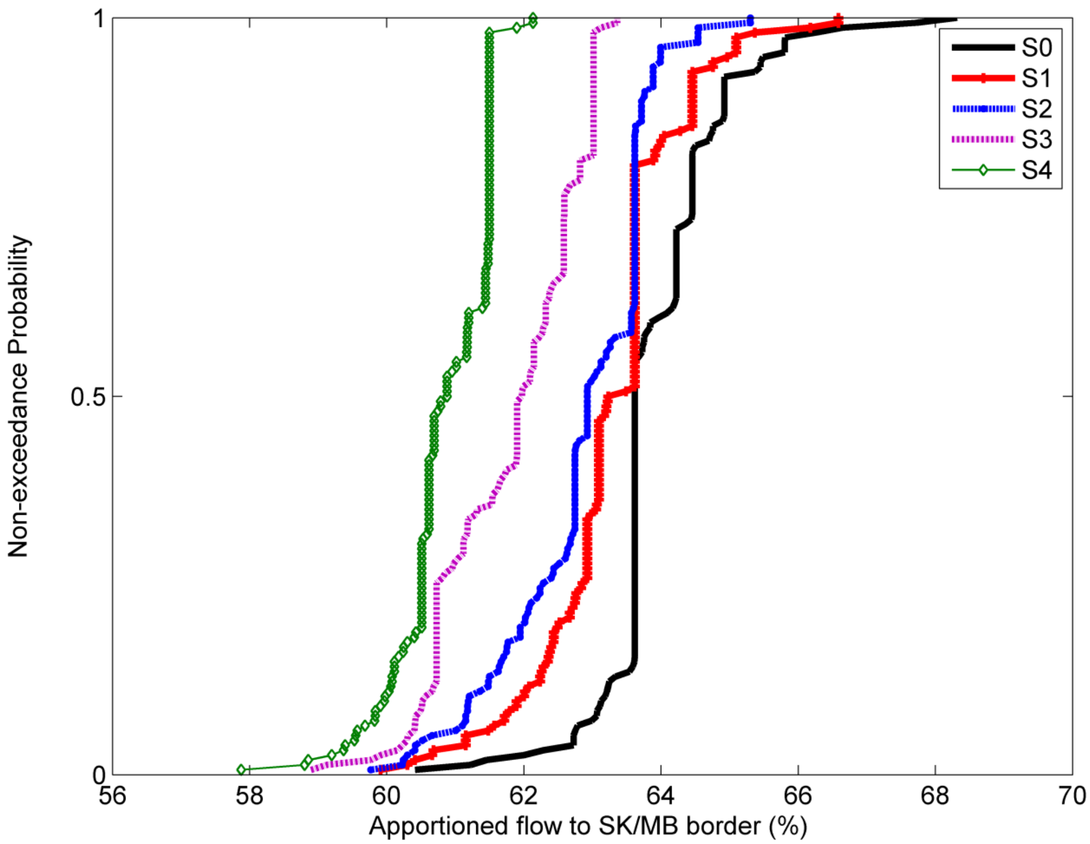

Figure 3-7 Minimum non-exceedance probability for apportioned flow to Manitoba under scenarios of irrigation development and changing water availability condition.

3.5.4 Effects on the Saskatchewan River Delta

The effect of changes in upstream water availability and irrigation development on the SRD was investigated in terms of the changes in the SR flood frequency. According to the SWSA (SWSA, 2015), SR flows that exceed 2500 m^3/s can cause flooding in the Cumberland House area. In fact, the SRD has experienced weekly flows well above 2500 m^3/s in the past. For instance, during the 2013 Alberta floods, the SRD had an average flow of 3700 m^3/s in the last week of June and many people were evacuated from Cumberland House (CBC News, 2013). To explore the changes in SR flood frequency under alternative scenarios, for each realization the number of years for which SR flow exceeds 2500 m^3/s was counted. For each of (-4, -25%), (0, 0), and (4, 25%) cases, the percentage of the 200 realizations that experience flooding was calculated and presented in Table 3-1 for various annual flood occurrences.

Table 3-1 highlights that flood frequency is more sensitive to changes in water availability conditions than increased irrigation. When the SSR and NSR flows are increased by 25% and shifted four weeks later, an increase in irrigation area does not change the SR flood frequency. Even under (0, 0) conditions, irrigation expansion slightly affects the flood frequency. The noticeable decline in flood frequency within all (-4, -25%) cases compared to (0, 0) and (4, 25%) conditions indicates that decreased upstream water availability conditions can highly reduce the number of peak SR flows. Furthermore, in cell (-4, -25%), irrigation expansion can considerably influence the SR peak flow frequency. For instance, under the (-4, -25%) case, the percentage of realizations with at least one year of flooding under the S4 scenario (9%) is about half of the percentage of realizations in S0 (20%) – for additional results, see Section C.2 of Appendix C.

3.5.5 Effects on economic production

In this section, the impacts of uncertain water availability and agricultural development plans on the economics of irrigated agriculture and hydropower are assessed and explained below. Results showed that, under current operational management, the industrial and mining demands are insensitive to changes in water availability and irrigation expansion.

Table 3-1 Percentage of realizations in each scenario that SR flow exceeds 2500 (m^3/s).

Scenarios and Irrigation expansion level		Flow conditions		Percentage of realizations that SR flow exceeds 2500 (m^3/s) during 31 years			
		Changes in annual flow volume (%)	Shift in annual peak flow timing (week)	At least 1 year	At least 2 years	At least 3 years	At least 4 years
S0	current	25%	4	49%	11%	4%	3%
S1	100%	25%	4	49%	11%	4%	3%
S2	200%	25%	4	49%	11%	4%	3%
S3	300%	25%	4	49%	10%	4%	3%
S4	400%	25%	4	49%	10%	4%	3%
S0	current	0	0	42%	9%	3%	1%
S1	100%	0	0	42%	10%	2%	1%
S2	200%	0	0	42%	9%	2%	1%
S3	300%	0	0	41%	9%	2%	1%
S4	400%	0	0	41%	8%	2%	1%
S0	current	-25%	-4	20%	3%	2%	0%
S1	100%	-25%	-4	17%	2%	1%	0%
S2	200%	-25%	-4	14%	2%	1%	0%
S3	300%	-25%	-4	12%	1%	1%	0%
S4	400%	-25%	-4	9%	1%	0%	0%

The mean annual Net Benefit (NB) for irrigated agriculture was calculated based on the irrigation expansion scenarios, water availability, and cost and revenue values in a way similar to that presented in Hassanzadeh et al. (2014). In brief, the NB is calculated by subtracting the total cost of production from the total revenue generated by the irrigated agriculture sector. Figure 3-8 presents the results of NBs for different combinations of water availability and irrigation expansion using response surfaces (Jones, 2001). In this figure, mean, minimum, and maximum NBs for irrigated agriculture are taken across 200 realizations and are presented in the upper, middle, and lower rows, respectively. The results indicate that changes in flow volume influence the NBs related to irrigated agriculture, but the impact of changes in peak timing is limited. Figure 3-8 also implies that as the irrigated area increases (moving from left to right), the risk of failure in meeting the agricultural demand rises. For instance, depending on the water availability conditions, the mean NB for irrigated agriculture in S4 changes between $10 and $65 million. Considering the minimum NBs and moving from S0 to S4, the NBs can become negative when the water availability declines. The minimum NB in S4 varies between -$50 and $50 million and the NBs become negative as a result of a 5% drop in historical annual volume. Considering these results, it can be argued that farmers might get a low but fairly stable income under the current irrigation area (S0) and variable (including dry) water availability conditions. However, as shown in Figure 3-8, by increasing the irrigated area 400%, farmers' revenue might increase significantly in wet years and decrease, with possibly negative NBs, in dry years. This issue indicates that making decisions for expanding agricultural area can be challenging and requires additional risk-based analysis.

The same analysis was repeated to explore changes in mean annual hydropower NBs. Similar to Figure 3-8, results are shown in Figure 3-9 for mean, minimum, and maximum hydropower NBs in different rows. Hydropower NBs are sensitive to changes in annual volume but not to changes in timing of the annual peak. In addition, increasing irrigated area has a smaller impact on annual hydropower NBs than changes in streamflow regime. Any increase in irrigation area decreases summer hydropower NBs. However, as the peak hydropower production is in winter, irrigation demand does not significantly lower the annual hydropower NBs.

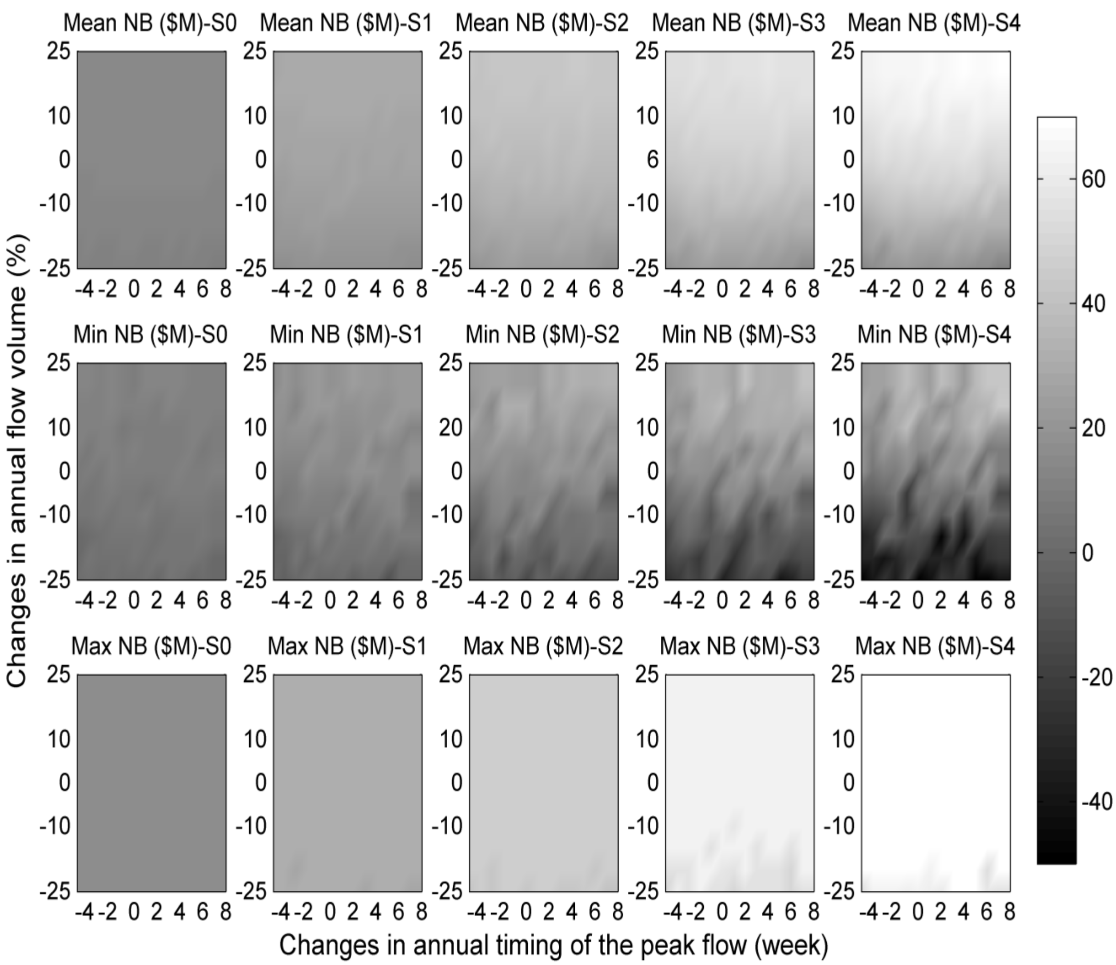

Figure 3-8 Sensitivity of irrigated agriculture's net benefit (NB) to changes in water availability and level of irrigation development.

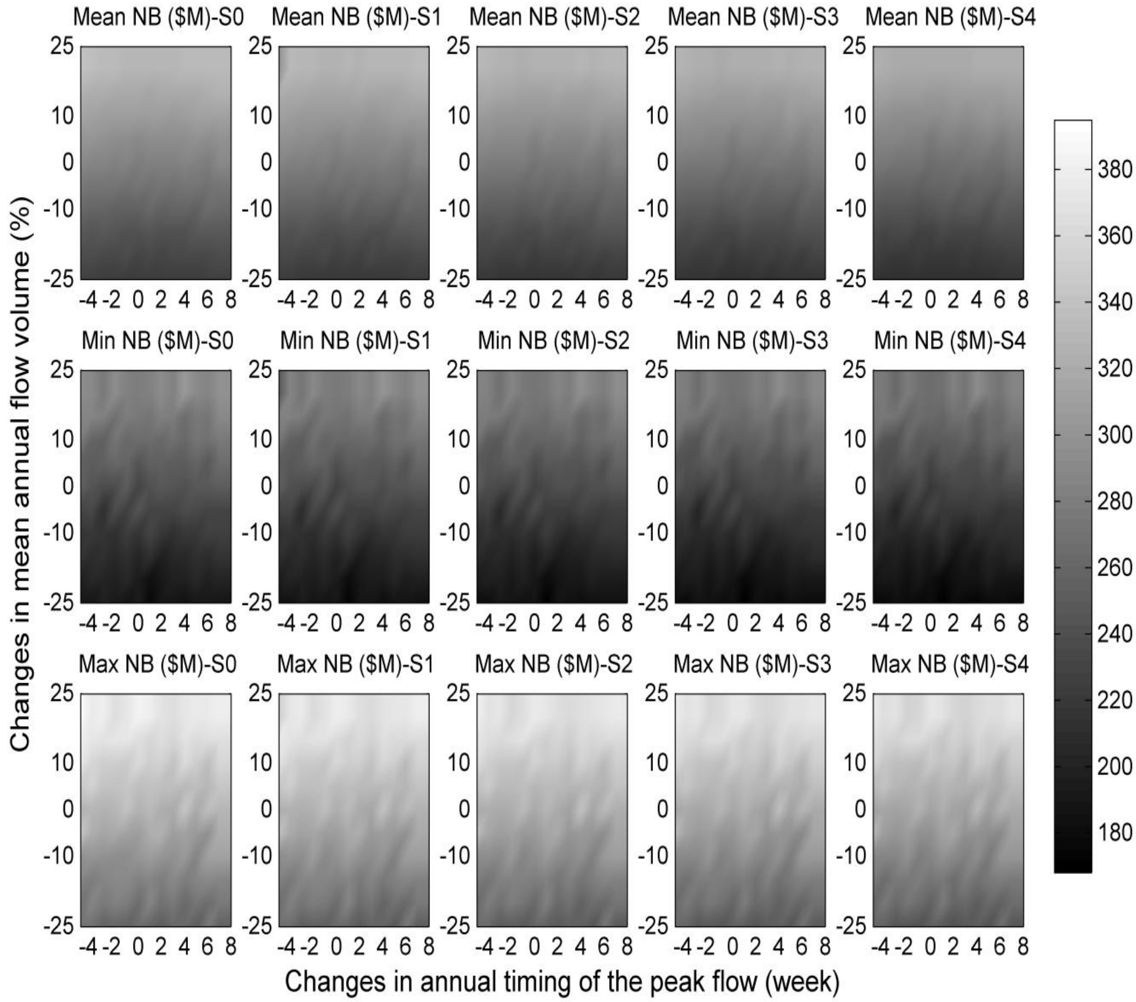

Figure 3-9 Sensitivity of hydropower's NBs to changes in water availability and level of irrigation development.

3.5.6 Sensitivity of the system to streamflow reconstruction pathway

The presented results in this study were obtained under independently generated SSR flows and estimated NSR flows based on the SSR flows. In this section, the reconstruction exercise was repeated to estimate SSR flows based on generated NSR flows to assess the sensitivity of the system to streamflow reconstruction pathway. Simulation results for various sectors imply that the overall pattern of variation in sectorial behavior under changing streamflow regime is consistent under both reconstruction pathways. The magnitude of variation, however, can be slightly different using alternative reconstruction pathways. For instance, Figure 3-10 shows the changes in percentage for hydropower NBs when SSR was reconstructed based on NSR relative to the conditions when NSR was reconstructed based on SSR for current irrigation level. Figure 3-10 shows that the maximum difference between the two reconstruction pathways is about 5% and it happens during the extreme flow conditions. There is a systematic difference between two pathways under the extreme high/low flow conditions. For the remaining flow conditions, the difference between two pathways is just due to random error.

3.5.7 Sensitivity of the water resource system to changes in climate conditions

Here a simple sensitivity analysis was done to illustrate the impact of changing climate conditions on irrigation demand as well as the water resource system. Based on literature (e.g., Pomeroy et al., 2009), a -10% to 15% change in annual precipitation and an increase in annual temperature by a maximum of 3.5^0C is projected for this region. Monte-Carlo sampling was used to generate 200 realizations of changes in temperature up to 3.5^0C and decreases in precipitation up to 10%. To present the worst case conditions, results here are only shown for a 400% increase in irrigated area and low flow conditions from cell (-4, -25%). In $SWAMP_{SK}$, changes in climate conditions directly affect the irrigation water demand through changes in crop water requirement and soil moisture. Changes in precipitation and temperature (through evaporation) also directly impact the reservoir water level. Water availability for irrigation demand is supported by Lake

Diefenbaker, therefore, changes in the irrigation demand indirectly affect the Lake Diefenbaker water level. The $SWAMP_{SK}$ was run using the selected scenarios of change.

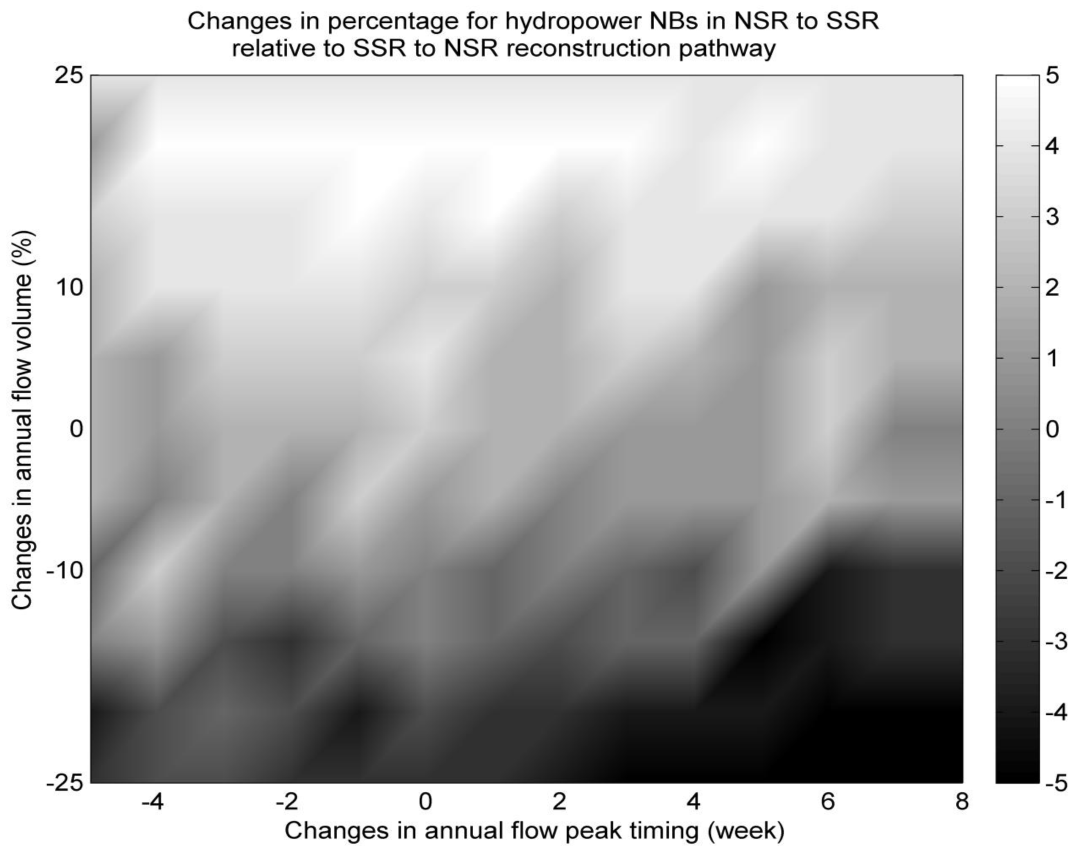

Figure 3-10 Changes in percentage for hydropower NBs in NSR to SSR relative to SSR to NSR reconstruction pathway.

Figure 3-11 shows simulation results for Lake Diefenbaker and downstream SSR flow towards Saskatoon. Changes in these two system variables can sufficiently represent the state of the water supply system condition. Results based on historical climate conditions as well as changes in climate conditions are shown with a dashed line and an envelope (solid line), respectively. Figure 3-11 shows that under low flow conditions and large irrigated area, the combination of increasing temperature and decreasing precipitation can slightly affect the Lake

Diefenbaker water level in dry times only. Changes in climate conditions insignificantly affect downstream SSR flows. This quick sensitivity analysis indicates that assessing the sensitivity of irrigation demand, as well as the water resource system to changes in climate conditions might be valuable but it is not as important as the changes in incoming streamflows from a regional water resource management perspective in the SaskRB.

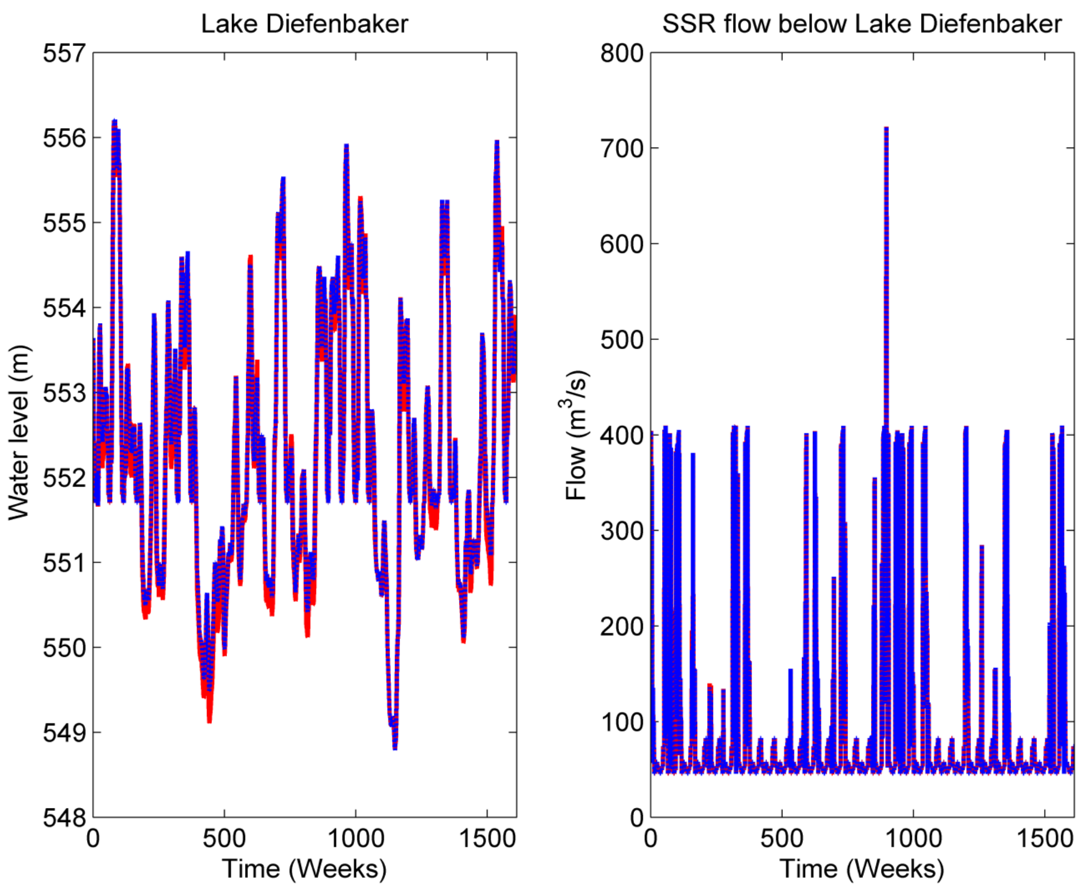

Figure 3-11 Sensitivity of Lake Diefenbaker water level and downstream SSR flow to increase in temperature up to 3.5^0C and decrease in precipitation up to 10% under flow conditions of low annual volume with early annual peak timing, and a 400% increase in irrigated area. Dashed line and envelope (solid line) show results for historical and changing climate conditions, respectively.

3.6 Discussion and Conclusions

This study applies a water resource vulnerability assessment by linking notions for uncertain water availability with an integrated water resources model. The process includes producing a wide range of flows stochastically, corresponding to feasible current and future streamflow characteristics, and using this ensemble of synthetic flows with a hydro-economic model for comprehensive analysis of water resource systems. To illustrate this, part of the Saskatchewan River Basin, in Saskatchewan, Canada, was selected and the flows at the Alberta/Saskatchewan border were generated using a stochastic reconstruction algorithm that can accommodate potential shifts in flow characteristics. This envelope of synthetic flows, including 30,800 realizations, was further combined with current proposals for irrigation development (up to 400% increase in irrigated area) to assess the impact of the development on the water resource system under changing water availability conditions.

Using $SWAMP_{SK}$ as an integrated water resource management model, it was found that changes in flow regime and irrigation development can affect various water sectors in Saskatchewan; however, the source and magnitude of impacts varies greatly between sectors. Although reduction in water availability and large agricultural expansion decrease the water apportionment to downstream province of Manitoba, the outflow from Saskatchewan satisfies the inter-provincial commitments under all scenarios of water availability and irrigation expansion. The results also showed that the impacts of changing flow regime are more significant than increase in irrigation area for the Saskatchewan River Delta (SRD), located downstream. An increase in irrigation area can, however, considerably reduce the frequency of peak flows in the SRD when the upstream flows decline (e.g., flows are dropped by 25%). The hydropower sector is likely to be more affected by the changes in flow regime than an increase in irrigated agriculture. The results showed that increasing the irrigated area does not always result in an increase in net revenue for this sector, which depends on the flow regime and the level of increase in irrigation area. It is acknowledged that irrigation expansion has environmental impacts on surface and groundwater, however, these impacts were not included in this study. The results call for analysis to investigate the possibility of adaptive water resource system management practices to minimize risks and/or maximize the benefit for water uses in Saskatchewan. Thus the response surfaces and the stress test analysis could be updated under alternative policy decisions to visualize the consequences of various management options.

There are some limitations in this study that suggest the need for future improvements. It was assumed that changes in the timing of the annual peak and annual flow volume can sufficiently describe all possible changes in streamflow conditions. There are several other properties, such as changes in seasonal, annual and inter-annual variability that can trigger system vulnerability. A linear regression was used to generate NSR flows based on synthetic SSR flows. Improved methods for preservation of spatial correlation can be sought in the future. The operational policies in the reservoirs were kept the same throughout the 31-year of simulation period. This may not be true in reality as water managers would apply adaptive management strategies when facing changes in the streamflow characteristics. It is also suggested to use climate projection a long with the stochastic realizations to identify the chance of possible future outcomes similar to the study by Brown et al. (2012). Furthermore, results of 200 realizations for each cell were represented by a single value. For future analysis, it is recommended to present the variability and associated risk for the entire ensemble of realizations in each cell.

In summary, it is concluded that the framework for producing alternative water availability conditions, analysis of their effects on system vulnerability using an integrated water resources model, and presentation of results in simple response surfaces for various municipal, environmental, and economic impacts, can be a viable and helpful approach towards assessment of the performance of water resource systems under water uncertain water availability in other regions of the globe.

3.7 Acknowledgments

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Chapter 4 - A risk-based framework for water resource management under changing water availability, policy options, and irrigation expansion

This chapter is currently under review in *Advances in Water Resources* Journal.

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Contribution of the PhD candidate

The initial conceptualization for probabilistic presentation of performance measures under changing conditions was proposed by Dr. Amin Elshorbagy. The PhD candidate significantly extended this idea and leveraged it to a novel approach to quantify the contributions of various changing conditions to the overall risk in system performance. The candidate carried out the computational development, simulations, and drafted the manuscript. All co-authors commented and edited of the manuscript.

Contribution of this chapter to the overall study

In the previous chapter, the sensitivity of the system performance to changing water availability and alternative irrigation levels was explored under business-as-usual water policy.

This chapter extends that analysis to also explore various options within the policy space, with the greater objective of proposing policies that minimize the undesired risk in system performance under changing conditions. The chapter therefore is a logical and methodological continuation of the use of the $SWAMP_{SK}$, developed in Chapter 2, and the stochastic streamflow framework adopted in Chapters 3. In this chapter, empirical probability distributions of system performance are used to quantify the single and joint contribution of changing conditions on variation in system behavior, which can consequently result in proposing decisions that result in minimization of undesired change in water resource system performance.

4.1 Abstract

Long-term water resource management requires the capacity to evaluate alternative policy options in the face of various sources of uncertainty in the future conditions of a water resource system. This study proposes a generic framework for determining the relative change in probabilistic characteristics of system performance – namely overall and sectorial net benefits – as a result of changing water availability, policy options and irrigation expansion. These probabilistic characteristics can be considered to represent the risk of failure in the system performance due to the uncertainty in future conditions. Quantifying the relative change in the performance risk can provide a basis for understanding the effects of multiple changing conditions on the system behavior. This framework was applied to the water resource system of the Saskatchewan River Basin (SaskRB) in Saskatchewan, Canada. A "bottom-up" flow reconstruction algorithm was used to generate multiple realizations for water availability within a feasible range of change in streamflow characteristics. Consistent with observed data and projected change in streamflow characteristics, the historical streamflow was perturbed to stochastically generate feasible future flow sequences, based on various combinations of changing annual flow volume and timing of the annual peak. In addition, five alternative policy options, with and without potential irrigation expansion, were considered. All configurations of water availability, policy decisions and irrigation expansion options were fed into a hydro-economic water resource system model to obtain empirical probability distributions for system performance under the considered changes. Results show that no one specific policy can provide the optimal option for water resource management under all flow conditions. In addition, it was found that the joint impacts of changing water availability, policy and irrigation expansion on

system performance are complex nonlinear functions of changes in individual drivers. The proposed risk-based framework can be linked to any water resource system assessment scheme to quantify the risk in system performance under changing conditions, with the larger goal of proposing alternative policy options to address future uncertainties.

4.2 Introduction

Regional characteristics of water availability can change due to both warming climate and human activities. As a result, water resource managers are increasingly faced with the need to make decisions in the face of uncertain water availability conditions (Milly et al., 2008). Due to the uncertainty in water availability, modern water resource management has evolved from searching for optimal solutions under known water futures to evaluating potential system vulnerabilities and choosing policy decisions that avoid maladaptation (Stainforth et al., 2007; Lempert and Groves, 2010; Whateley et al., 2014). This involves analyzing different water availability conditions in conjunction with alternative management plans, with the larger goal of understanding critical thresholds, trade-offs among water sectors and possibilities for improving system performance under uncertain future conditions.

Methodologically, long-term assessments of water resource systems under uncertain future conditions have developed mainly around “top-down” and “bottom-up” approaches (Wilby and Dessai, 2010). In the commonly used top-down assessments, future streamflow conditions are determined using hydrological models that are forced with downscaled climate variables obtained from projections of one or more Global Climate Models (GCMs; see e.g.

Lauri et al., 2012; Georgakakos et al., 2012; Karamouz et al., 2013; Borgomeo et al., 2014). Application examples range from proposing operational rule curves for reservoirs (e.g., Raje and Mujumdar et al., 2010; Eum and Simonovic, 2010) to investigating the suitability of economic investment plans (e.g., Arndt et al., 2011). The key challenge in this approach is the large uncertainty that propagates from GCMs, downscaling methods and hydrological models to the assessment of water resource systems (e.g. Kundzewicz et al., 2008; Beven 2011; Nazemi and Wheater, 2014a).

Alternatively, bottom-up assessments have been proposed to assess the potential vulnerabilities in a water resource system without direct use of climate model projections (e.g. Prudhomme et al., 2010; Lempert et al., 2010; Steinschneider and Brown, 2012). Compared to the top-down approach, bottom-up schemes are more methodologically diverse. Examples include Robust Decision Making (Lempert, 2006), Decision Scaling (Brown et al., 2011b), Info-Gap Analysis (Ben-Haim 2006), and Many-Objective Robust Decision Making (Kasprzyk et al., 2013). Typically “response surfaces” or “system vulnerability maps” are derived for system performance conditioned on possible changes in climate variables. These maps are then employed to identify critical climate conditions that cause vulnerability in the system. Finally, using GCM projections, the likelihood of the critical climate conditions and climate-related risk in the water resource system can be explored (Brown et al., 2011a). This risk-based framework has been increasingly used to assess system vulnerability under changing climate (Brown et al., 2012; Steinschneider et al. 2015a) and to propose alternative policy decisions under uncertain climate conditions (Moody and Brown, 2013; Ghile et al. 2014; Steinschneider et al. 2015b).

Despite these developments, there are certain limitations in current bottom-up risk-based approaches. From the technical perspective, response surfaces are commonly obtained using hydrological models; as a result, the uncertainty in hydrological models is embedded in the vulnerability maps (Wheater and Gober, 2013). It has been argued that uncertainties in hydrological models may be equal to or greater than those associated with climate models (Steinschneider and Brown, 2014) and can add substantial uncertainty to the assessment of water resource systems (Nazemi and Wheater, 2014b). Moreover, hydrological models are still limited in representing changes in water availability as a result of human interventions (Nazemi and Wheater, 2015a, b). To overcome these uncertainties, "fully" bottom-up schemes have been developed to generate streamflow conditions directly as a function of potential changes in streamflow characteristics (e.g. Nazemi et al., 2013; Hassanzadeh et al., 2015). However, the risk in system performance is often described as a function of climate or policy only; therefore, the joint impacts of these drivers and the impact of other sources of change are yet to be addressed.

From the management perspective, understanding the relative contribution of each changing driver and combination of multiple drivers is important and can identify how various changing conditions can intensify or suppress the overall or sectorial performance of water resource systems.

The objective of this study is to propose a framework to quantify relative changes in the system performance corresponding to possible changes in water availability, policy options and irrigation expansion. A fully bottom-up approach, proposed by Nazemi et al. (2013) and further validated by Hassanzadeh et al. (2015), was used to stochastically generate various streamflow conditions. The reconstructed flows were further combined with various policy options, and irrigation expansion levels. Accordingly, the variation in system performance corresponding to different combinations of changing factors in the system was obtained. This was considered as a basis to derive the relative contribution of each changing factor on the performance of the system. Section 4.3 describes the proposed framework. In Section 4.4, the case study and methodology are briefly described. Results and analyses are given in Section 4.5, followed by summary and conclusions in Section 4.6.

4.3 Description of the risk-based framework

Here, uncertain future conditions refer to a situation in which the exact knowledge about future water availability and demand as well as policy is not available. This uncertainty can be represented by a range of feasible future conditions. By conditioning the water resource system to these feasible futures, a range of possible system performance can be consequently obtained. Here "risk" refers to the empirical probability of system performance (and hence the chance of system failure) under changing conditions and can be obtained using multiple simulations of the system under feasible scenarios of change. Figure 4-1 shows the workflow of the proposed framework for evaluating the risk in the performance of water resource systems under changing water availability, policy options, and irrigation expansion. Three fundamental elements are required. The central part is a hydro-economic model, with which system performance can be characterized under different management options and water availability conditions. System performance can be measured using various behavioral indicators (see Hashimoto et al., 1982), or calculated only based on economic cost benefit (Griffin, 1998). Here, we used economic-based indictors, namely sectorial and provincial net benefits. Sectorial net benefits are used to reveal the trade-offs between competing sectors; whereas Provincial Net Benefit (PNB) is used to reveal the overall system performance at the scale of the Province of Saskatchewan.

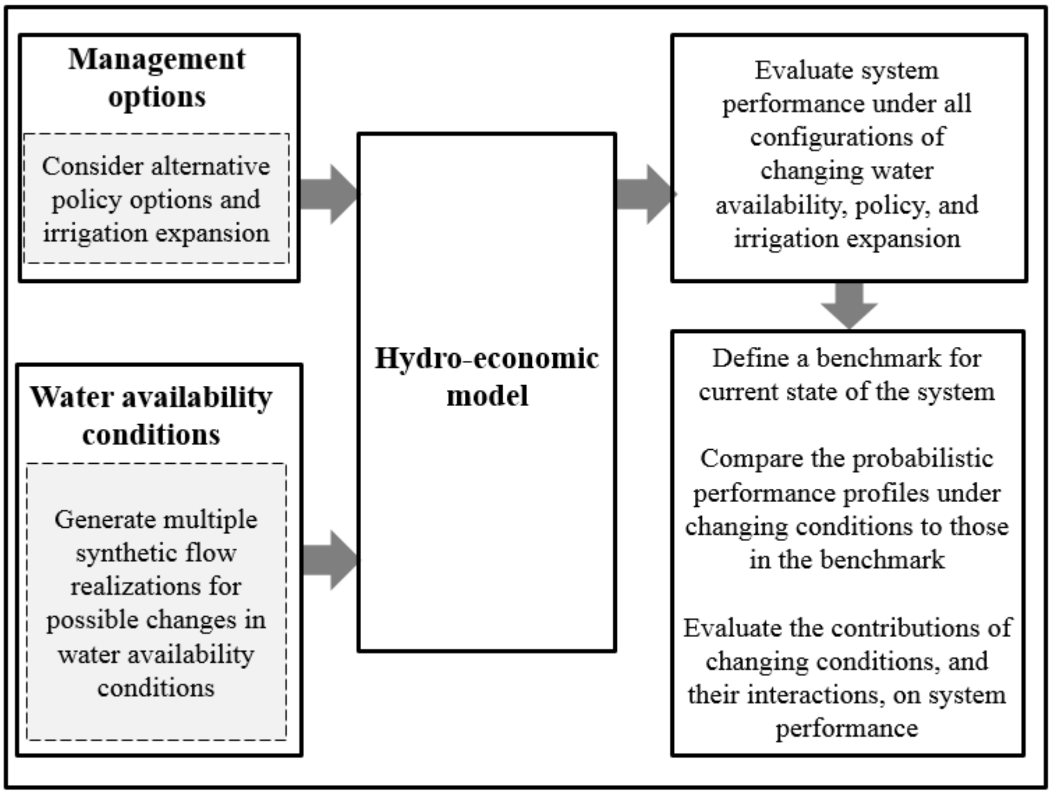

Figure 4-1 The workflow of the proposed risk-based framework for water resource management under uncertain future conditions

The hydro-economic model should be then linked to a set of options that represent alternative management decisions (e.g. different levels of irrigation expansion and/or policy option etc.) as well as changing water availability. The latter should accommodate both natural variability as well as regime changes due to climate change and/or human interventions. Such streamflow conditions can be obtained from various stochastic flow reconstruction schemes given feasible assumptions concerning changes in the historical flow conditions. By feeding multiple management and water availability realizations to the hydro-economic model, multiple performance measures can be obtained under various combinations of changing factors. These performance measures can be described using various probabilistic indicators obtained from their Empirical Distributions (EDs). These probabilistic profiles can represent the risk in system performance under an ensemble of the realizations of change in system conditions.

Using these probabilistic (or risk) profiles, the relative contribution of changing factors to system performance can be quantified. This includes first defining a benchmark condition for the current state of the system, i.e. a specific flow regime, irrigation expansion level, and policy option. This is the state by which the changes in system performance are defined. Second, for any given performance measures, the Empirical Cumulative Distribution Functions (ECDFs) corresponding to changing conditions and the benchmark conditions can be compared. For any percentile (i.e. probability), the relative change in benchmark performance can be calculated using Equation 4.1:

$$\Delta_p = \frac{q_{c,p} - q_{b,p}}{q_{b,p}} \times 100 \qquad (4.1)$$

where p is percentile, and Δ_p presents the percentage of change with respect to the benchmark state of the system in performance criterion due to changing conditions. $q_{c,p}$ and $q_{b,p}$ correspond to quantiles (q) in the ECDFs for changing (c) and benchmark (b) conditions, respectively. For instance, the relative change in median performance ensemble (Δ_{50}) is the relative percentage difference between the median performance under change scenario and the benchmark condition. Using this approach, not only can the relative risk in the system performance due to separate and/or joint effects of changing factors be quantified, but also interactions among changing conditions in increasing/decreasing the risk in the system performance can be investigated. This approach, therefore, provides a generic framework to evaluate the effect of management options on changing the benchmark risk profile under different combinations of flow regime and development level.

4.4 Case study and methodology

4.4.1 The Saskatchewan River Basin in Saskatchewan

This study considers the water resource system in the Saskatchewan portion of the Saskatchewan River Basin (SaskRB). A simple schematic is presented in Figure 4-2 with squares representing reservoirs, arrows showing channel flows, main river channels shown with thick arrows, and key water diversions shown with thin arrows. In brief, the water resource system is built around the Southern and Northern inflows of the Saskatchewan River (SSR, NSR, respectively), entering from the upstream province of Alberta. Although the mean annual inflows from NSR and SSR are similar (213 and 215 m^3/s, respectively), the majority of water users are located around the highly regulated SSR. Lake Diefenbaker, the largest reservoir in the Canadian Prairies, is the key streamflow regulator in the SSR. This multi-purpose reservoir was built in

1959, with maximum storage capacity of 9400 Million Cubic Meters (MCM), and plays a key role in the water resource system. The Saskatchewan Water Security Agency (SWSA) operates Lake Diefenbaker for flood control and conservation purposes, hydropower and recreation, as well as various demands including irrigation, which is the largest consumptive water use in the system (Martz et al., 2007). Environmental constraints considered by SWSA include local habitats and downstream flows. Under current management policy, hydropower plants located at Lake Diefenbaker's Coteau Creek dam, and the downstream Nipawin, and E.B. Campbell dams provide the highest economic benefit from water allocation in the system (Martz et al., 2007). There is a provincial interest to sustain and increase the level of hydropower production (SWSA, 2012). Irrigated agriculture presents the second largest NB in the province. Here, the PNB is defined as the sum of irrigated agriculture and hydropower NBs. Further details of the study area are presented in Hassanzadeh et al. (2014; 2015).

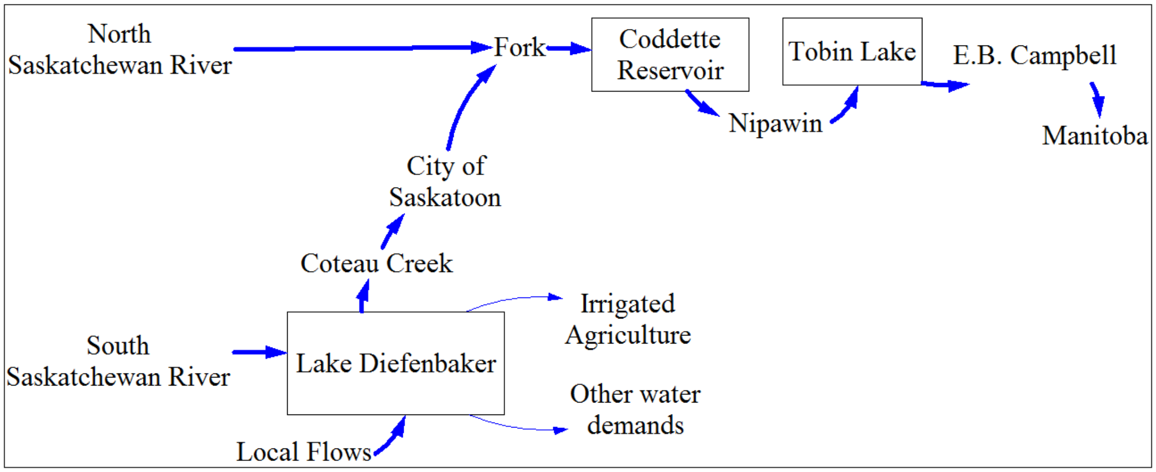

Figure 4-2 A simple schematic of the water resource system in Saskatchewan including main flows, reservoirs, and water demands

There are two major challenges associated with water management in Saskatchewan. First, the water resource system in Saskatchewan is largely dependent on the incoming flows from the upstream province of Alberta. As a result, changes in the upstream inflow regimes can significantly affect the performance of Saskatchewan's water resource system. Such changes in the upstream inflow regime are expected in future due to climate change (e.g., Martz et al., 20007; Sauchyn et al., 2009) and potential management interventions. Two annual streamflow characteristics, namely annual flow volume and timing of the annual peak, are convenient indicators of the annual flow regime and are particularly important for water resource management in the prairies, due to high irrigation demand concentrated in a relatively short growing season (Nazemi et al. 2013; Hassanzadeh et al., 2015). Second, Saskatchewan is undergoing major socio-economic development, which can further translate into increasing water stress in time and space. In particular, the Government of Saskatchewan is investigating increasing the current irrigated area in the province by 400% to enable agriculture to play a major role in global food security (Saskatchewan Ministry of Agriculture, 2012); as a result, it is important to evaluate the long-term effects of irrigation expansion on the water resource system.

4.4.2 Management alternatives

To cope with challenges in the water resource management in Saskatchewan, SWSA (2015a) have suggested revisiting policy alternatives to manage the water resource system. Multiple long-term planning options were defined by considering regional watershed hydrology, management constraints, monetary benefits and certain operational objectives. As Lake Diefenbaker plays a key role in operating the system, these planning objectives were manifested through Lake Diefenbaker operational rule curves, which were mainly defined by minimum, ideal, and Feasible Storage Levels (FSLs) for reservoir operation (SWSA, 2015b). Figure 4-3 shows expected rule curves for current (business-as-usual) and suggested revised policies. These rule curves were used in this study as policy alternatives for managing the water resource system under current and expanded irrigation and are briefly explained below.

4.4.2.1 Business-As-Usual (BAU): The current operational policy for Lake Diefenbaker is targeted to fulfill multiple purposes such as hydropower production, recreation, flood control, and meeting regional water demands. For flood control, the objective is to fill Lake Diefenbaker during the high flow spring snowmelt as well as summer extreme runoff from Alberta, coinciding with high rainfall (SWSA, 2015a). The stored water is depleted in fall and winter until the following spring refill period (SWSA, 2012). This policy aims to balance all regional objectives with a reasonable degree of equity.

4.4.2.2 Flood Control (FC): This policy gives priority to flood control and attempts to make reservoir storage available for high floods during late spring/early summer. In the fall/winter period, flows from Lake Diefenbaker are released to provide the desirable water level for April, while meeting downstream flow constraints.

4.4.2.3 Supply Security (SS): This policy gives priority to water storage in the reservoir to maintain the water availability during possible dry periods. In this policy, the purpose is to keep the reservoir water level as near to FSL as possible. Flows from Lake Diefenbaker toward downstream can be released in fall/winter up to a level that ensures a high probability of refilling to FSL by end of June/mid-July.

4.4.2.4 Recreation (R): This policy aims to keep Lake Diefenbaker water level at a fairly high and stable level to enable boating and more general accessibility of Lake Diefenbaker during the recreation season. During fall/winter drawdowns, minimum water levels are fixed to ensure a high probability of being at or above the desirable recreation level for spring. Starting from early spring, the policy aims at refilling the reservoir to the new and desired FSL. Once the FSL is reached, outflows would be managed to maintain the reservoir as close to the FSL as possible.

4.4.2.5 Hydropower Maximization (HM): The objective is to generate the maximum hydropower energy, while supporting other water users. Hydropower maximization policy avoids reservoir spillage, and producing power when it has the highest value.

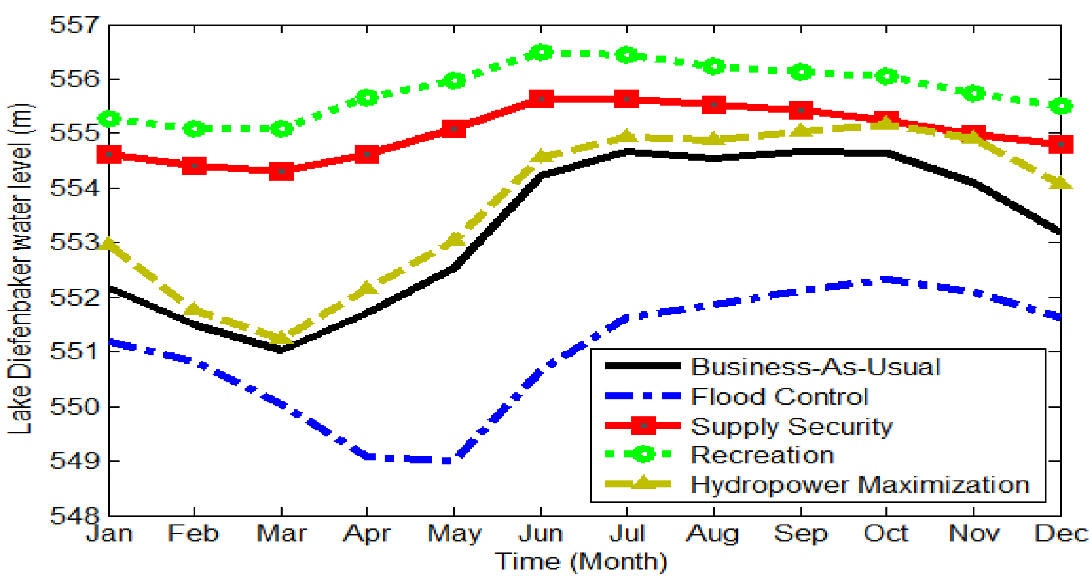

Figure 4-3 Current and suggested rule curves for operating Lake Diefenbaker

4.4.3 An integrated water resource system model for Saskatchewan

Simulation of the water resource system in Saskatchewan was carried out using the $SWAMP_{SK}$ - an integrated water resource system model developed by Hassanzadeh et al. (2014) and further used by Hassanzadeh et al. (2015). In brief, $SWAMP_{SK}$ simulates the water resource system under given water availability and policy conditions and calculates both economic and behavioural performance indicators associated with the operation of the water resource system. The model was developed using the System Dynamics approach (Forrester, 1961), which is an extensively used method in water resource systems modeling literature (e.g. Ahmad and Simonovic, 2004; Elshorbagy et al., 2005; Hjorth and Bagheri, 2006; Madani and Mariño, 2009; Winz et al., 2009; Simonovic, 2009; Madani 2010; Hassanzadeh et al, 2012; Dawadi and Ahmad, 2012; Mirchi et al., 2012; Gohari et al., 2013; Wu et al., 2013; Gohari et al., 2014; Chen and Wei, 2014; Li et al., 2015; Sahin et al., 2015). The temporal resolution of $SWAMP_{SK}$ is weekly and simulations cover the period 1980-2010. The operational rule curves and water allocation priorities corresponding to alternative policies were directly implemented in the model using variables and functions (see Hassanzadeh et al., 2014). The simulation results include water supply for the municipal, environmental, industrial, irrigation, and hydropower sectors as well as river flows and reservoir levels. The economic evaluation sub-model estimates the economic benefit for hydropower and irrigated agriculture.

4.4.4 Synthetic streamflow generation

A large ensemble of synthetic streamflow series, including a wide range of changes in timing of the annual peak and annual volume of NSR and SSR flows at Alberta/Saskatchewan (AB/SK) border was generated without incorporating any hydrological model. The ensemble generation scheme was introduced by Nazemi et al. (2013) and was used in this study to reconstruct multiple weekly realizations for water availability conditions under predefined annual volume and timing of the peak. This method involves two steps. First, pre-specified shifts in timing of the annual peak as well as changes in annual flow volume were incorporated into weekly streamflow quantiles using the quantile mapping framework (Panofsky and Brier, 1968). Second, new random samples were generated using the empirical distribution associated with the perturbed streamflow quantiles. The sampling scheme maintains the temporal dependence within streamflow time series using a copula approach (Nazemi and Elshorbagy, 2012). The feasible range for changes in annual streamflow characteristics was selected based on the recent literature on streamflow projection in the SaskRB and the system's geographical properties (e.g., Pomeroy et al., 2009; Lapp et al., 2009; North Saskatchewan Watershed Alliance, 2008). The entire range for changes in flow regime includes -5 to +8 weeks changes in timing of the annual peak and -25% to +25% changes in annual volume of flow. This range is referred here as feasible Water Availability Change (WAC). Considering one week and 5% increment in annual peak timing and volume, the WAC can be divided into 154 possible water availability conditions (14 × 11, respectively). For each WAC condition, 200 realizations of 31 year flow sequences were stochastically generated to present random variability in each flow regime. In total, 30,800 synthetic flow realizations were generated. Similar to Hassanzedeh et al. (2015), each specific water availability scenario is represented by an (x, y) pair, or a "cell", in which x represents the shift in annual peak timing in weeks and y the relative change in annual flow volume. Three specific flow regime, i.e. (0, 0), (-4, -25%), and (4, 25%) were selected to investigate the effect of random variability in specific flow regimes and to benchmark the system performance for various flow conditions. These three flow conditions exemplify flow conditions of no-change, drier with earlier peak, and wetter with delayed peak, respectively. In the rest of this paper, these three flow conditions are referred as “specific water availability conditions”. Figure 4-4 shows the expected long-term hydrographs for the reconstructed SSR inflow to Saskatchewan at the AB/SK border for the specific flow conditions.

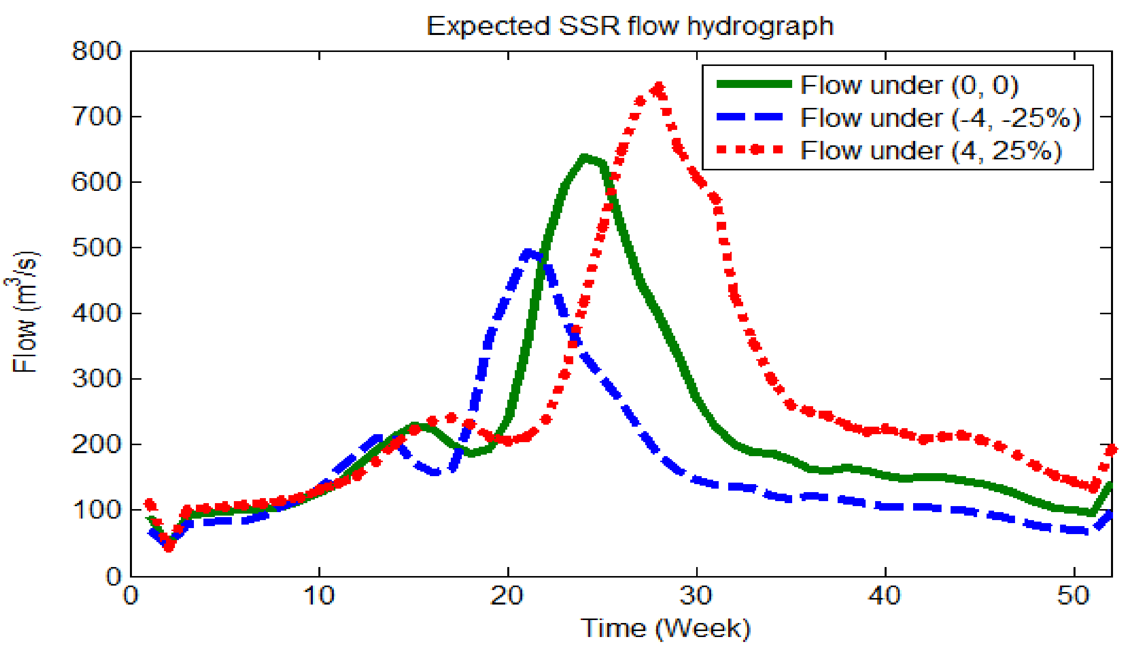

Figure 4-4 Annual expected hydrographs for the SSR streamflow at the AB/SK border for historical (0, 0), as well as selected dry (-4, -25%), and wet (4, 25%) flow regimes

4.5 Results and discussion

In this section, the proposed risk-based framework is presented and discussed using economic performance indicators in the Saskatchewan portion of the SaskRB. It should be noted that the assessment framework can be applied to any other system and/or sectors. Figure 4-5 shows the response surfaces for the mean annual PNBs ($M) over a thirty one year period, obtained through the applied bottom-up approach, under changing water availability regime, policy options and irrigation expansion. These response surfaces provide a holistic view of the pattern of variation in PNBs due to combination of changing factors. For instance, it is obvious that the system is more sensitive to changes in flow volume rather than changes in annual peak timing. Nonetheless, the vulnerability maps only show the results for one statistical measure (here the expected PNBs over 200 realizations in each cell); as a result, the risk in system performance due to random variability in each cell as well as the entire range of WAC is concealed. In addition, such response surfaces do not provide any information regarding the how various changing factors interact and together change the system performance. This highlights the necessity for a generic approach for improved understanding of the system behavior under uncertainty.

To illustrate the effect of changing conditions on the system performance, various EDs are used. First, the performance risk profiles for hydropower NBs under the three specific flow conditions and the various policy options are shown and the effect of irrigation expansion on the hydropower NBs is investigated. Such analysis leads to a greater understanding of how different policies affect the performance of the water resource system in specific flow conditions. Second, the impacts of policy options with and without irrigation expansion are explored for both hydropower and agricultural net benefit to highlight possible trade-offs as a result of changing flow conditions and/or increased level of irrigated agriculture. This assessment leads to understanding the impacts of alternative policy options, and irrigation expansion on sectorial vulnerability in specific flow conditions. Finally, the risk profiles for PNBs are analyzed to quantify the relative contribution of each factor in altering the risk in PNB values. This leads to the presentation of a generic decision making framework under all possible combination of changing water availability conditions, policy options and irrigation expansion.

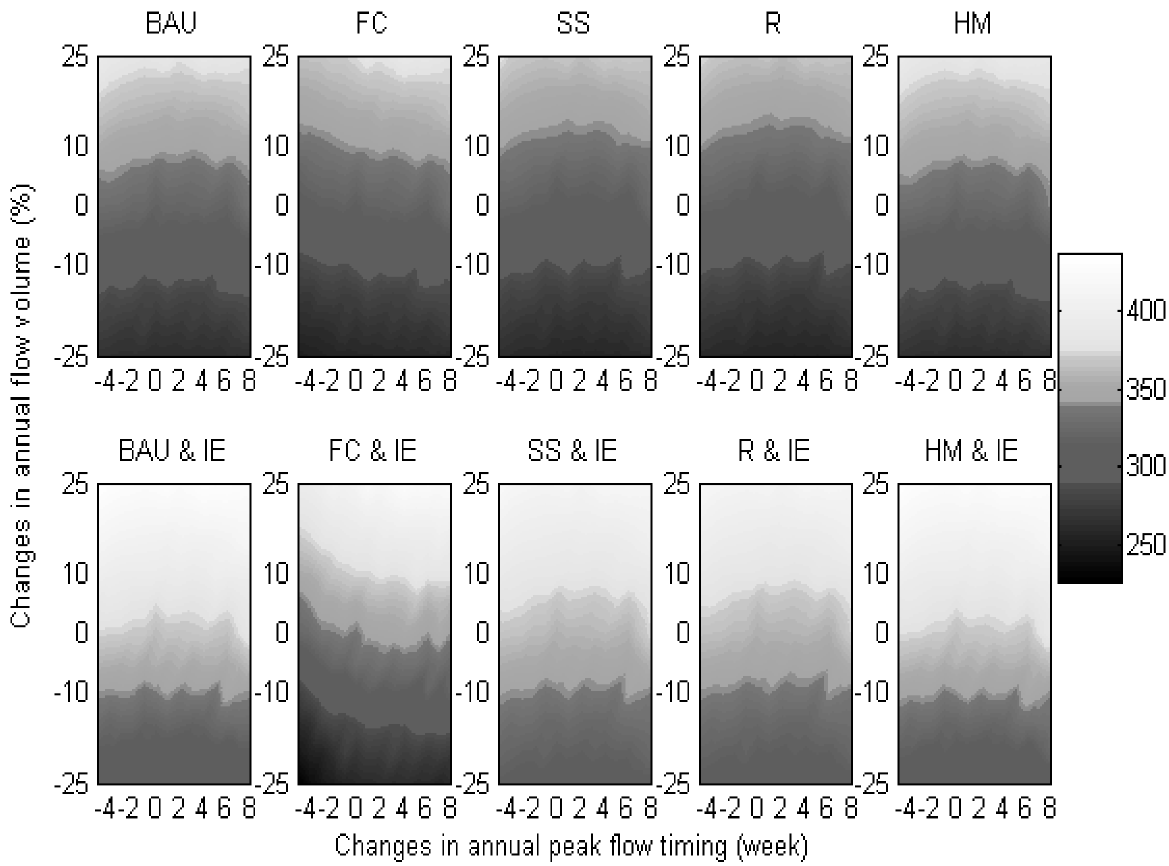

Figure 4-5 Response surfaces for PNB ($M) under changing water availability and policy options without (first row) and with (second row) irrigation expansion (IE). The magnitude of PNB is shown in colour according to the right hand side colour-scale.

4.5.1 Risk profiles for hydropower net benefit under specific water availability conditions and changing policy options, with and without irrigation expansion

Figure 4-6 shows the Empirical Probability Distribution Functions (EPDFs) for hydropower NB under the specific wet, historical, and dry conditions. These EPDFs were obtained under the BAU policy and current level of irrigation and characterize the effect of random variability under the three specific water availability conditions. The mean, variance, and coefficient of variation (CV) associated with these profiles are presented in the first row of Table 4-1 – see below. It was noted that different flow conditions do not necessarily present similar risk profiles. For example, the (4, 25%) provides the lowest CV in comparison to (-4, -25%), and (0, 0), indicating that wetter water availability conditions lead to smaller uncertainty in hydropower NB.

Table 4-1 Statistical characteristics of the hydropower NB under selected dry, no-change and wet flow conditions and changing policy options

Management options		Specific water availability conditions								
		Dry (-4, -25%)			Historical (0, 0)			Wet (4, 25%)		
		mean ($M)	variance ($M)^2	CV -	mean ($M)	Variance ($M)^2	CV -	mean ($M)	variance ($M)^2	CV -
Current irrigation area	BAU	252	185	0.05	303	241	0.05	355	156	0.04
	FC	243	153	0.05	299	247	0.05	356	176	0.04
	SS	247	146	0.05	294	188	0.05	343	129	0.03
	R	245	145	0.05	293	187	0.05	341	129	0.03
	HM	253	196	0.06	305	249	0.05	358	156	0.03
Expanded irrigation area	BAU	239	179	0.06	291	251	0.05	345	186	0.04

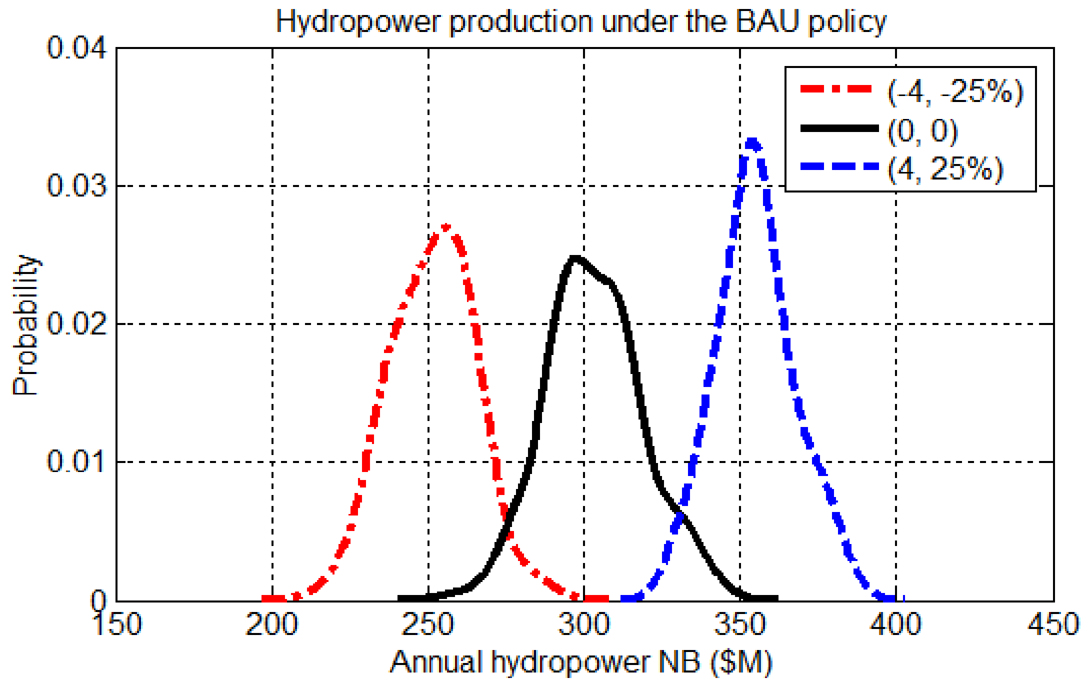

Figure 4-6 Probabilistic risk profiles for hydropower NB under the BAU policy, current level of irrigation and selected streamflow conditions

Figure 4-7 illustrates the effect of irrigation expansion on hydropower net benefit under selected wet – (4, 25%), no-change – (0, 0), as well as dry – (-4, -25%) water availability conditions (see Section D.1 of the Appendix D for the results related to whole ensemble of water availability change). Hydropower NBs for the current and expanded irrigated agriculture are shown with solid and dashed lines, respectively. Comparison between mean values for the BAU policy under the specific flow conditions (see Table 4-1) implies that expanding irrigated areas decreases the expected value of hydropower benefit by 5%, 3% and 4% in dry, historical, and wet flow conditions, respectively. However, by changing the flow conditions from historical to the drier condition, the hydropower NB under current and expanded irrigation loses on average about

17.5%. This implies firstly that the hydropower sector is much less compromised if irrigated area is expanded under unchanged flow conditions; and secondly, that the effect of changing flow conditions is far more than expanding the irrigated area. Thus, the hydropower sector should be more concerned about the impact of natural variability and changing flow conditions.

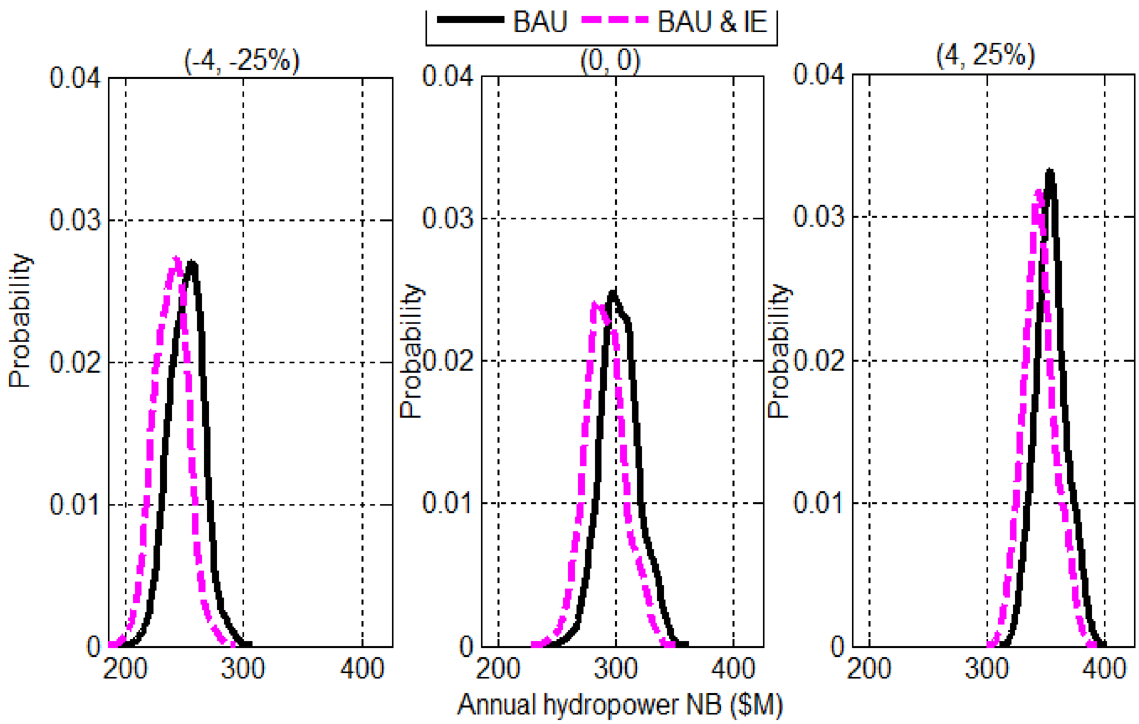

Figure 4-7 Risk profiles for hydropower net benefit under the BAU policy with and without irrigation expansion (IE) for the three specific water availability conditions

Figure 4-8 shows the risk profiles for hydropower NB under the three water availability conditions and the five alternative policy options. Simple statistical properties of these risk profiles are provided in Table 4-1. As illustrated in Figure 4-8 and Table 4-1, given wet, no-change, and dry conditions, alternative management options result in different risk profiles and/or performance statistics. As can be expected, relative preference between planning options can change based on water availability conditions.

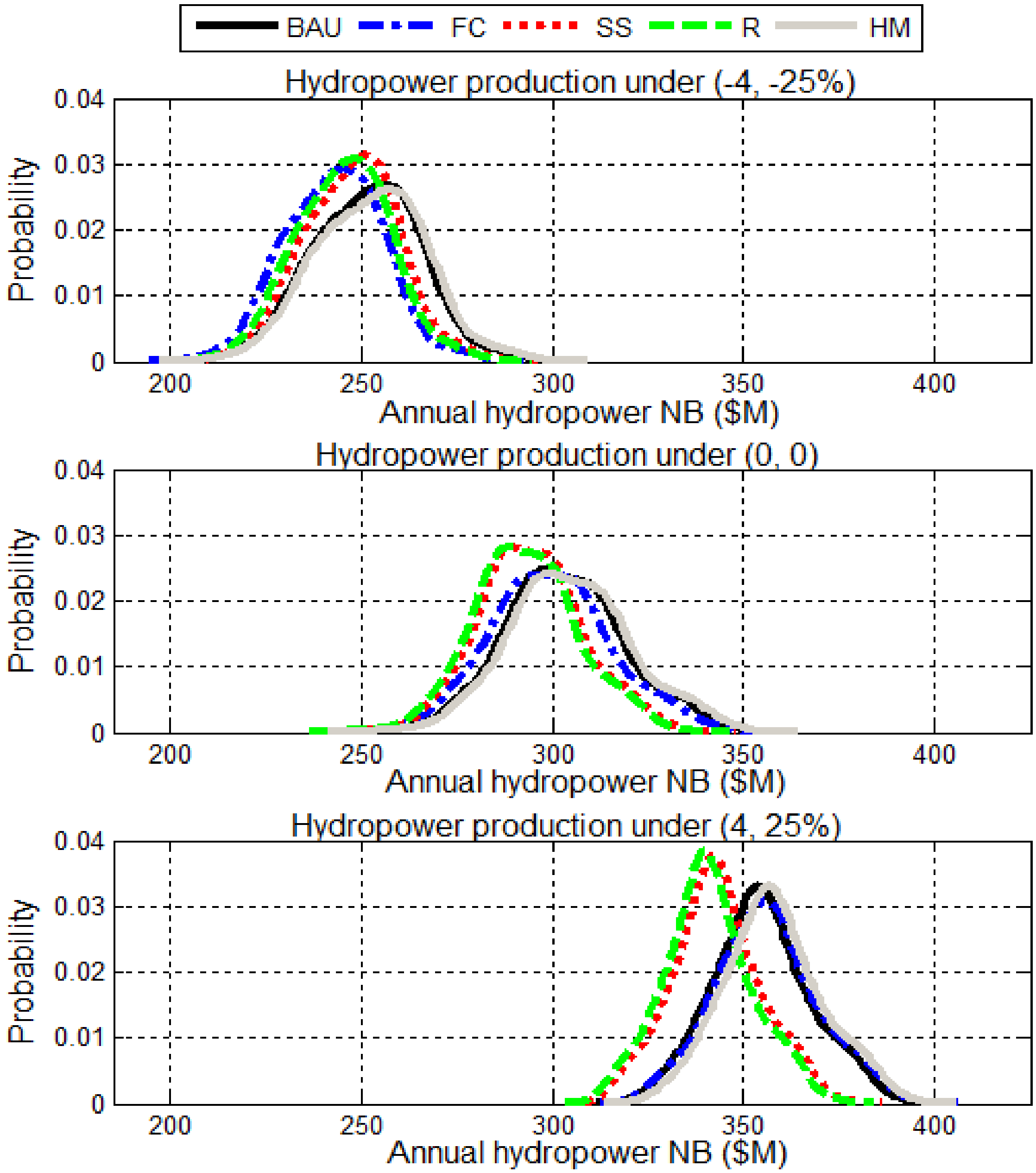

Figure 4-8 Risk profiles for hydropower NB profiles under the three specific flow conditions and changing policy options

4.5.2 Trade-offs between hydropower and irrigated agriculture under the specific flow conditions and changing policy, with and without irrigation expansion

Trade-offs between irrigated agriculture and hydropower net benefits for various planning options with and without irrigation expansion are shown in Figure 4-9. Each row shows results for random variability under one of the specific water availability conditions. In the ideal condition, when irrigation demands are fully met, the irrigated agriculture leads to 14.8 $M and 75 $M NB annually under current and expanded irrigated area, respectively. In brief, under the current irrigation area (large circles in the figure), Figure 4-9 shows that the policies related to SS and R can fully meet irrigation demand under all water availability conditions. While policies related to HM and BAU produce the highest hydropower net benefit, they can slightly reduce irrigation net benefit under the unexpanded irrigation level. The analysis shows that under current irrigation area and dry flow conditions, the BAU, HM and FC on average produce 14.5 $M, 13.6 $M, 9.6 $M for irrigation, which is 2%, 6%, and 35% lower compared to ideal irrigation production, respectively.

Considering the results under irrigation expansion (small grey circles in Figure 4-9), policies related to R and SS support maximum production under any flow conditions. Policies related to FC, HM and BAU decrease the agricultural net benefit; nonetheless, the magnitude of shortage depends also on the flow conditions. These three policies exacerbate the level of risk in performance particularly in dry flow conditions (see the spread of grey points in first row). Under dry conditions, the BAU, on average, produces 56$M and reduces the ideal net benefit of the expanded irrigated agriculture by more than 24%. FC and HM can even produce negative net benefit for irrigated agriculture under dry flows and expanded irrigation. They can produce 6$M and 44$M on average and can reduce ideal irrigation production by 92% and 41%, respectively. This analysis clearly presents sectorial competitions, in terms of statistical properties of economic gain/loss, depending on the policy option, level of expansion and flow conditions.

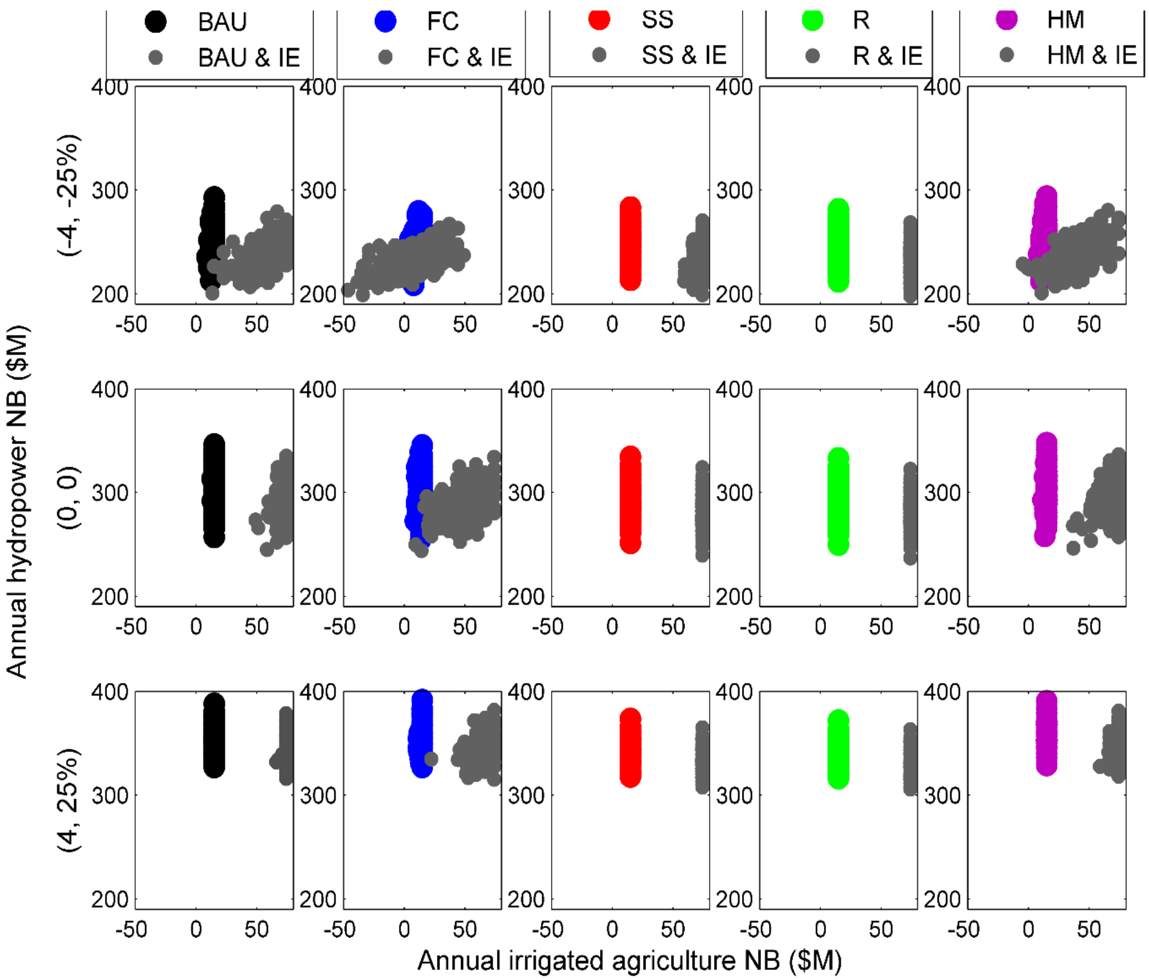

Figure 4-9 Trade-offs between irrigated agriculture and hydropower net benefits under specific dry, historical and wet water availability conditions and changing policy options with and without irrigation expansion

4.5.3 Relative effects of changing conditions on the provincial net benefit

Here, single and joint impacts of changing water availability, policy options, and irrigation expansion are determined using the relative changes in the PNBs obtained under the three benchmark flow conditions. These three benchmark conditions refer to the state of the system under specific water availability regimes in dry (-4, -25%), historical (0, 0), and wet (4, 25%) flow conditions, each with 200 realizations, combined with the BAU policy and current irrigation level.

Considering three options for change, i.e. flow conditions, policy decisions, and irrigation expansion, in total eight (2^3) possible options for change can be considered for each benchmark condition– see Table 4-2. It should be noted that water availability change implies considering changes, which are resulted due to the entire ensemble for WAC, 30,800 realizations, defined in Section 4.4.4. For instance, row II in Table 2 represents the state of the system under the entire range of water availability conditions with current irrigation area, and the BAU policy.

Similarly, changing policy options implies changes by one of the five policy options introduced in Section 4.4.2. PDFs of PNBs under these benchmark conditions were obtained and shown in Figure 4-10. These benchmark risk profiles can be compared to PNBs under any possible combination of change. For instance, Figures 4-11, 4-12, and 4-13 illustrate the benchmark PDFs against the risk profiles associated with increase in irrigation area, change in policy option (e.g., FC policy), and change in water availability conditions, respectively.

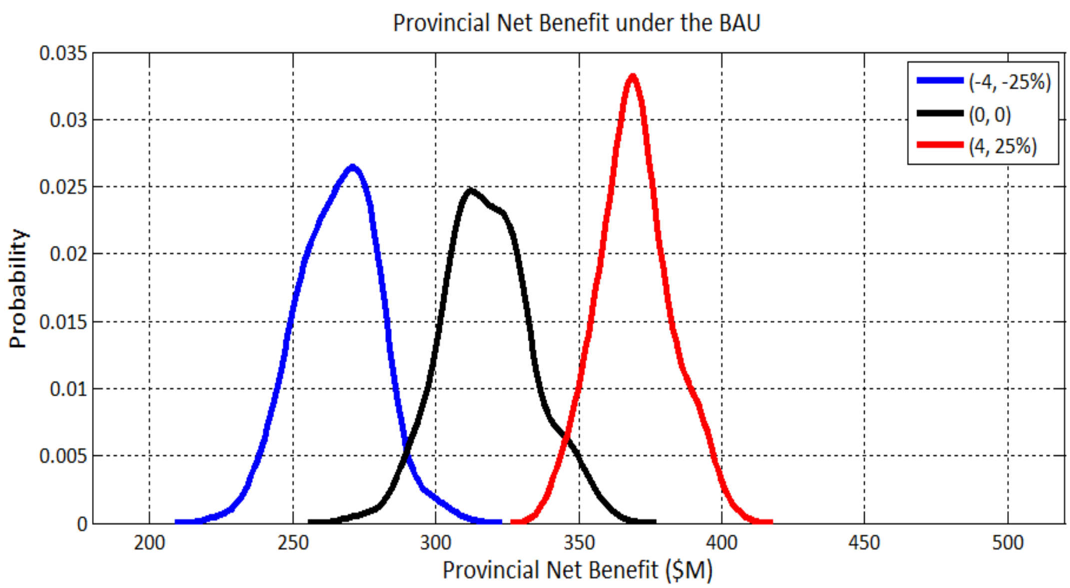

Figure 4-10 Benchmark risk profiles for PNBs under dry (-4, -25%), historical (0, 0), and wet (4, 25%) flow conditions

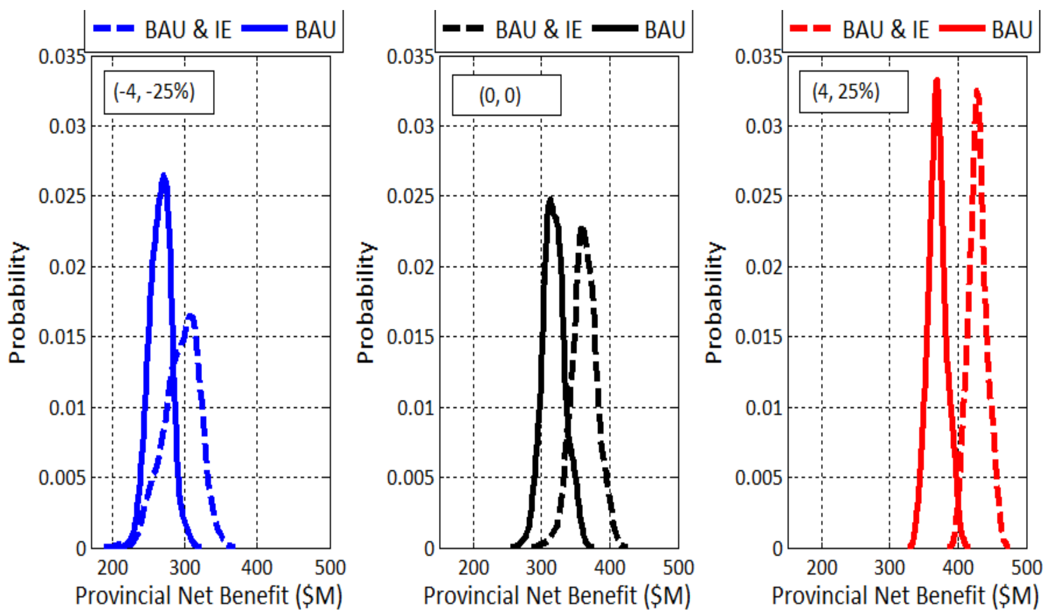

Figure 4-11 PNB risk profiles under benchmark and increase in irrigation area for (-4, -25%), (0, 0), and (4, 25%) flow conditions

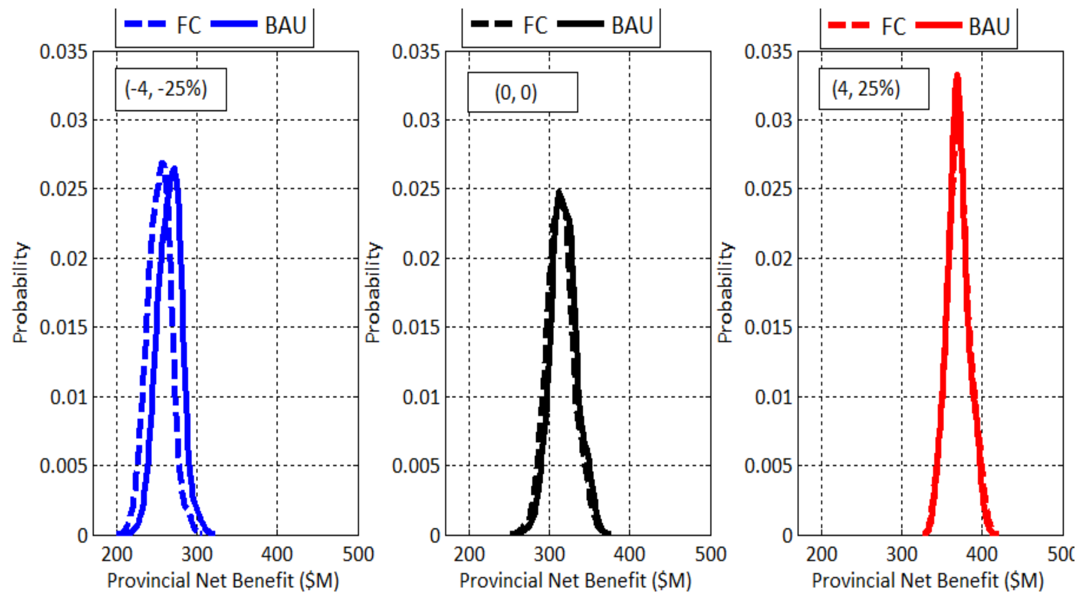

Figure 4-12 PNB risk profiles under benchmark and Flood Control (FC) policy for (-4, -25%), (0, 0), and (4, 25%) flow conditions

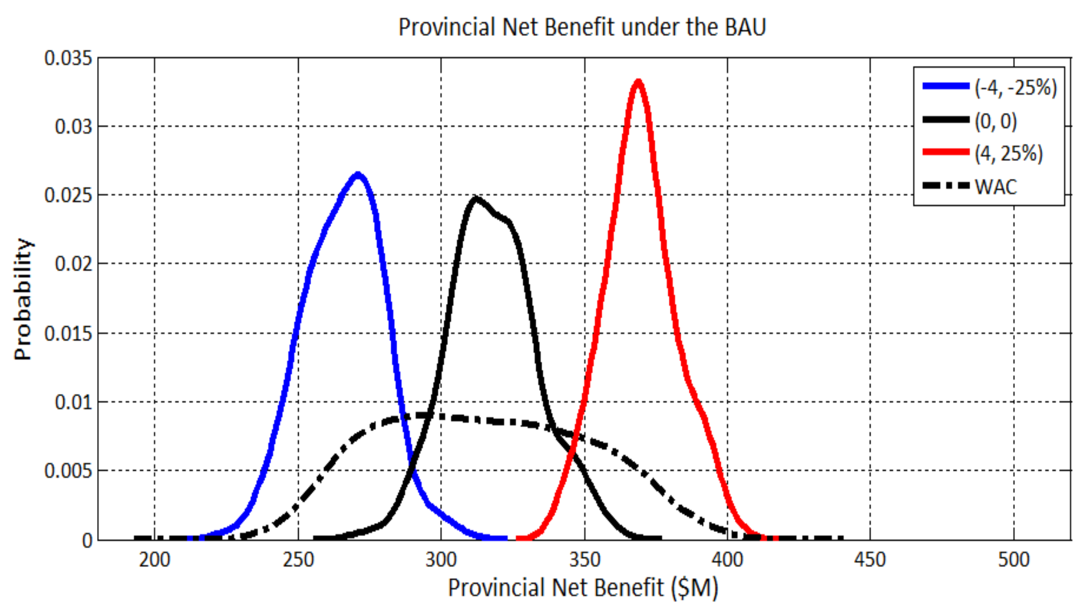

Figure 4-13 PNB risk profiles under benchmark in (-4, -25%), (0, 0), and (4, 25%) flow conditions versus the PNB risk profile under the entire range of change in water availabiltiy

Table 4-2 Possible options for changing water availability, policy options and irrigation expansion in benchmark conditions. The checkmark and x mark respectively present the changed and unchanged conditions.

Configurations	Water availability conditions	Policy option	Irrigation expansion
I (No change in benchmark)	✗	✗	✗
II	✗	✓	✗
III	✓	✗	✗
IV	✓	✓	✗
V	✗	✗	✓
VI	✓	✗	✓
VII	✗	✓	✓
VIII	✓	✓	✓

Apart from visual comparison, by obtaining the ECDFs for PNBs under individual and combination of changing conditions, the relative change in benchmark risk profiles can be quantified using Equation 4.1. Figure 4-14 shows relative changes in benchmark PNB quantiles under changing water availability and irrigation levels but no change in the BAU policy. This figure offers some interesting observations. First, irrigation expansion under each of the three benchmark conditions (the pink line) can change the PNB quantiles by -9% to 15%, 10% to 15%, and 15% to 18%, respectively. Only in the representative dry conditions (-4, -25%), irrigation expansion can decrease PNBs for percentiles smaller than 0.2. In other words, irrigation expansion could create at highest 20% chance to harm the provincial economy under extremely dry conditions. This is rather intuitive, as under the assumption of uniform probability of occurrence within the feasible WAC range, the (-4, -25%) benchmark conditions represents an extreme dry condition, in which changing water availability is more likely results in higher flow volume. As a result, changing the water availability within the feasible range in conjunction with irrigation expansion can likely bring positive economic effects.

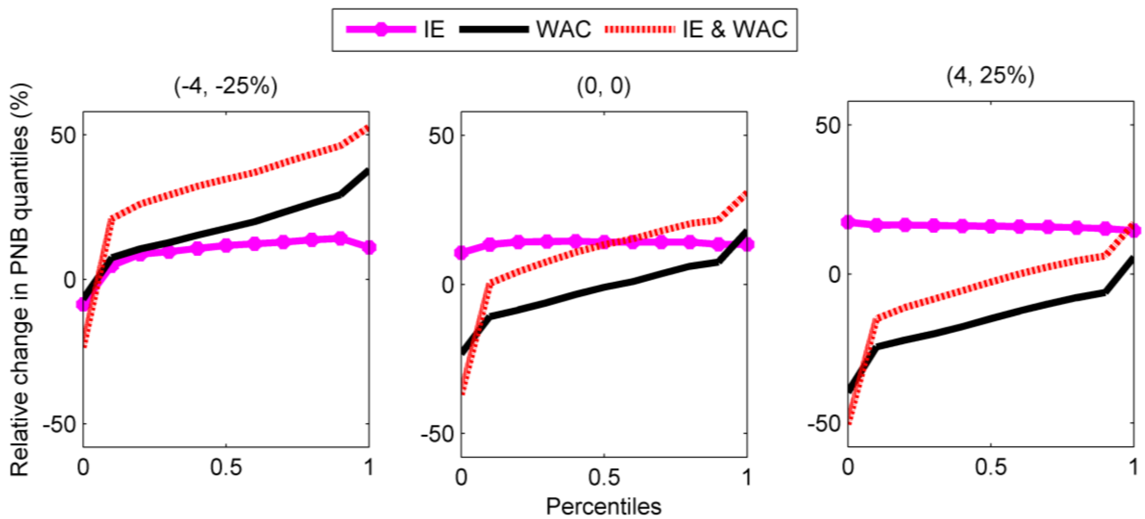

Figure 4-14 Relative changes in PNB quantiles due to changing water availability and irrigation expansion in the three specific benchmark conditions

The case is different for other benchmark conditions. For instance, during the specific wet flow condition, changing water availability can negatively impact PNB for more than 95% of the time. This is again intuitive, as the cell (4, 25%) presents a flow regime in which changing flow conditions would likely result in lower flow volume. To summarize, the comparison between dashed and solid lines, it can be argued that expanding irrigation can modestly improve PNBs under changing water availability conditions 80% of the time. The results also indicate that changes in relative risk due to joint effects of changing water availability and irrigation expansion are not necessarily equal to the sum of relative changes as a result of each driver.

4.5.4 Toward a risk-based water resource management under changing conditions

By extending the discussion above to consider policy options more generally, a generic basis for decision making under changing conditions can be obtained. A policy that provides the maximum positive (or minimum negative) impacts on the benchmark risk profile can be selected as the desired policy option under changing conditions. To illustrate this, Figure 4-15 shows relative impacts of changing policy options on benchmark PNBs with and without water availability change and irrigation expansion. Each row refers to relative changes in risk profiles due to changing conditions (i.e., one of the configurations V to VIII in Table 4-2), compared to one of the benchmark conditions. If irrigation expansion is not considered, the left and second left columns in Figure 4-15 show that alternative policy options result in similar relative change in PNBs under specific or changing WAC conditions. For instance in the three specific flow conditions, the relative difference in PNBs due to changing policy options are marginal and range from -6.5% to 2.5%, -4% to 0.6% and -4% to 1%, corresponding to selected dry, historical, and wet flow conditions, respectively.

In contrast, alternative policies perform differently if the irrigation expansion is considered. For example, under dry flow conditions, SS policy presents the highest PNB quantiles; however, in historical and wet flow conditions, the HM presents the highest PNBs.

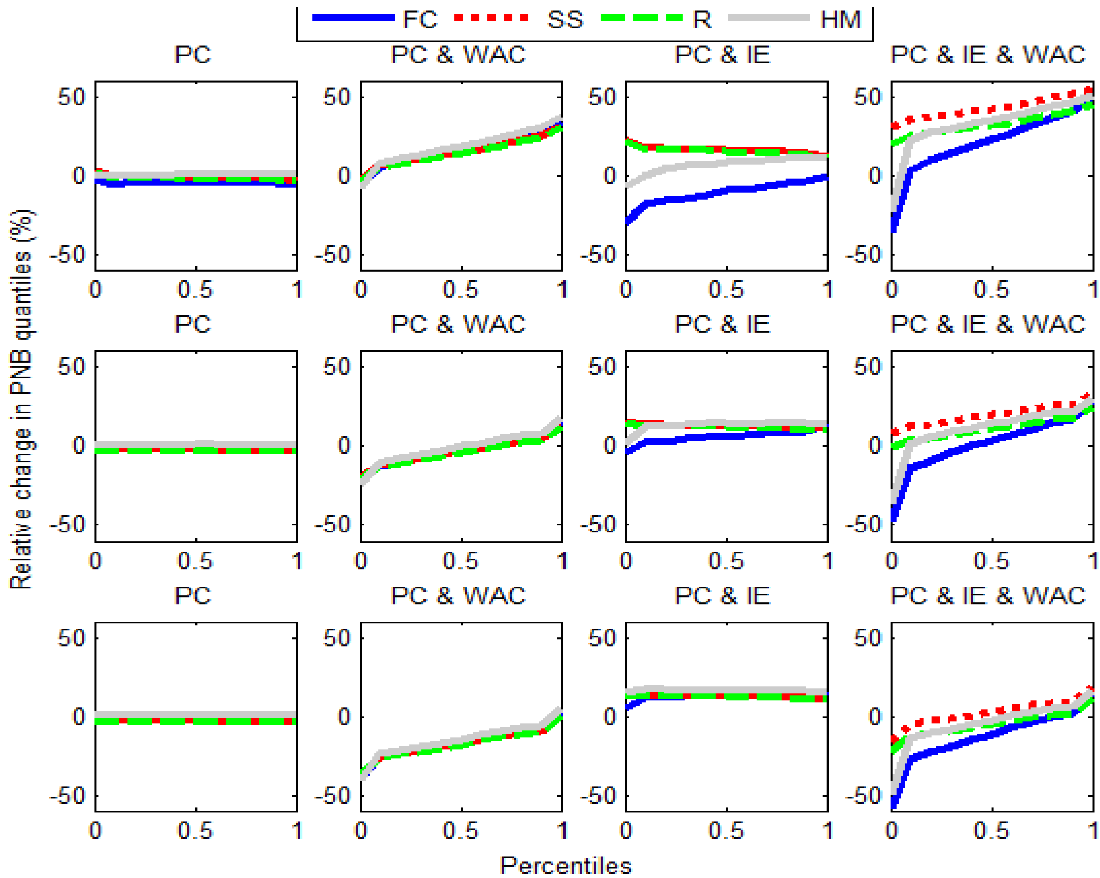

Figure 4-15 Relative change in PNB quantiles due to changing policy options (PC), water availability conditions (WAC), irrigation expansion (IE) and combination of these factors with respect to dry (top row), historical (middle row), and wet (bottom row) benchmarks. Alternative policies are related to FC (blue), SS (red), R (green) and HM (grey) and are compared with the BAU policy implemented in the benchmark conditions.

Similar to Figure 4-14, the joint impact of changing policy and irrigation expansion on PNBs is complex and is not a linear function of risk in PNBs due to individual drivers. Under all changing factors (right column), it is apparent that the SS policy presents the largest PNB quantiles. The HM presents the second largest PNB under most percentiles ($p>0.1$). The FC brings the lowest PNBs under all changing conditions. However if $p>0.9$, the behavior of FC policy becomes close to other policies particularly under historical and wet benchmark conditions.

It should be noted that the discussion provided above is generic and can be extended to any benchmark conditions that can refer to the current or future states of the system.

4.6 Summary and conclusions

This study proposes a generic framework to evaluate the risk in the performance of water resource systems to changing water availability, policy option, and irrigation expansion. This framework complements current bottom-up vulnerability assessments under changing conditions and can go beyond only accounting for climate risks. By differentiating between the impact of individual and joint drivers of change in the system, this framework provides an improved decision making procedure under uncertainty. To implement this framework, the SaskRB water resource system in Saskatchewan, Canada, was chosen. Synthetic flows at the AB/SK border were generated and used with five management alternatives with and without irrigation expansion. A hydro-economic model was used to simulate combinations of the policy options, irrigation expansion level (current or full), and water availability uncertainty. Our analyses indicate that under the current BAU policy, expanding irrigation area can change the PNB quantiles by -9% to 15%, 10% to 15% and 15% to 18% in dry, historical and wet flow conditions, respectively. It was also highlighted that under current irrigation level, HM policy acts slightly better than other policies in increasing the PNB quantiles. However, the differences between policy options in terms of changing the PNB quantiles is marginal and do not exceed

7% in this case. Nonetheless, as irrigation level increases, different policy options present significantly divergent levels of change in PNB quantiles. It was also noted that the joint impacts of changing conditions on the overall risk in system performance are complex and resemble nonlinear functions of individual drivers.

Although the underlying concept of risk profiles can be extended to any performance measure and provide an informative quantitative tool for policy-makers under uncertain water futures, our analyses have certain limitations, which can be resolved by future efforts. First, a fundamental assumption in this study is the fact that all possible water availability conditions were considered with identical probability of occurrence. Accordingly, different policies for alternative change in water availability (e.g., dry, no-change, and wet flow conditions) were suggested; however, the analysis was based on the equality in the occurrence of possible futures. This assumption can be easily relaxed by incorporating a top-down ensemble projections to identify the likelihood of water availability conditions in light of available climate and hydrological model. Second, the policy options were kept the same during the 31-year of simulation period. This may not be true in reality, as water managers normally apply adaptive management, when facing changes in the streamflow conditions. Third, the physical properties of the water resource system (e.g., irrigation efficiency, and canal capacity) as well as the demand were also assumed to be stationary through the simulation period, which can obviously change in the course of 31 years. It should be noted that a limited set of performance measures was considered in the analysis. However these could readily be expanded, for example to include non-economic criteria – see Section D.2 of Appendix D for an example. Furthermore, only five policy options were used to present long-term plans in the system. From a broader perspective, it might be interesting to generate a large ensemble of planning alternatives using Monte Carlo Sampling schemes to identify ensemble management options that can benefit various sectors under uncertain water availability. Our system dynamics based $SWAMP_{SK}$ model can be modified, without excessive efforts, to investigate the above-mentioned improvements. Regardless, the proposed framework has the potential to be broadly applied in water resource management and related decisions making processes under uncertainty. The presented risk-based framework can increase the level of awareness in decision making under changing water availability conditions and can be easily extended to other case studies, hydro-economic models and/or bottom-up vulnerability assessment schemes.

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Chapter 5 - Summary and Conclusions

5.1 Overview

Water resource management has been historically based on the assumption of stationarity in water availability, water demand, and socio-economic factors. Warming climate and human activities, however, have posed questions regarding the validity of this assumption (Milly et al., 2008). As a result, it has been discussed that mere consideration of historical data may not provide a suitable basis for water resource management under changing conditions (Beven, 2011). However, understanding the future state of water resources is extremely challenging due to uncertainties associated with the projections of future conditions. These uncertainties should be recognized and reduced for better management of water resource systems under changing conditions. To address this problem, various studies have suggested new developments that can improve our understanding of the system behavior and possible vulnerability to changing conditions. In brief, it is suggested to (1) understand the causal relationships among underlying system components and whole system behavior under changing conditions; (2) evaluate the sensitivity of the system to various natural and/or anthropogenic scenarios; and (3) propose policy decisions that can support robust system performance under considered changing conditions. In light of these suggestions, this thesis presents three developments towards improving water resource management under uncertainty. Each development has been presented in a separate chapter and has been pursued for application to the Saskatchewan River Basin (SaskRB) in Saskatchewan, which is a strategically important water resource system in western Canada.

The SaskRB supports water allocation for multiple sectors, among which hydropower and irrigated agriculture are key economic competitors. The SaskRB in Saskatchewan also provides the inflow to the Saskatchewan River Delta (SRD), the largest inland delta in North America, which has high cultural values to First Nations communities, and is an important ecosystem with one of the most biologically diverse habitat in Canada (Partners for Saskatchewan River Basin, 2008). Furthermore, the SaskRB in Saskatchewan must commit to the Master Agreement on Apportionment to deliver half of natural flows to the downstream province of Manitoba (Prairie Province Water Board, 2015).

In recent studies it has been argued that the SaskRB in Saskatchewan will face future water security challenges associated with changing water availability and socio-economic developments (e.g., Martz et al, 2007). Water availability in Saskatchewan depends on the incoming streamflow regimes in Alberta, where flow characteristics are subject to change due to warming climate and management decisions. Apart from changes in the incoming flows from Alberta, Saskatchewan itself is planning to increase its current irrigated area by 400% (Saskatchewan Ministry of Agriculture, 2012). The combination of changing inflows and increasing irrigation level in Saskatchewan can cause vulnerabilities in water resource management in Saskatchewan with direct and indirect impacts on water sectors, including the environment.

In response to these case-specific challenges this thesis explored the impacts of changing water availability and irrigation expansion on the performance of SaskRB in Saskatchewan.

Chapter 2 presented a sustainability-oriented integrated water resource system model for water allocation, management, and planning ($SWAMP_{SK}$), for the SaskRB in Saskatchewan. The developed model is based on the System Dynamics (Forrester, 1961) approach and includes (1) a water allocation, (2) an irrigation demand, and (3) an economic evaluation sub-models. The irrigation demand model estimates irrigation demand dynamically as a function of climate variables, soil moisture content and allocated crop water. Various reference evapotranspiration equations combined with soil-moisture accounting models were used to explore the sensitivity of the model. The economic evaluation sub-model was used to estimate the annual net benefit for the hydropower, irrigated agriculture and potash mine sectors, which revealed economic trade-offs among various water sectors. $SWAMP_{SK}$ can be used for better understanding of the system functionality and performance under uncertain future conditions.

Chapter 3 explored potential changes in the performance of the water resource system of the SaskRB under changing water availability and expanding irrigation. A fully-bottom up approach for assessing the potential vulnerabilities was employed. In brief, first, a feasible range of changes in the water availability regime of the system conditions was selected based on the available top-down assessments and geographic characteristics of the system. Changes in water availability were represented by perturbing the peak flow timing and mean annual streamflow volume at the Alberta/Saskatchewan border. Second, a large ensemble of streamflow realizations was generated stochastically. This was to provide a wide range of possible water availability conditions, on which the water resource system model can be conditioned. Finally, these streamflow realizations along with alternative scenarios of irrigation expansion were fed into the $SWAMP_{SK}$ to characterize the performance of the system under changing water availability and alternative irrigation expansion levels. The use of various hydro-economic performance measures enabled system stresses under changing conditions to be highlighted.

Chapter 4 proposed a novel framework to quantify the relative contribution of various changing conditions, such as water availability, policy options and irrigation expansion to the probabilistic characteristics of the system performance with a larger goal of providing a basis for decision making under uncertainty. The method can allow exploration of system performance under all possible combinations of changing conditions and can assist choosing polices that minimize undesired change in system performance. The fully bottom-up approach, implemented in Chapter 3, was used to represent changing water availability. Furthermore, five alternative policies for reservoir operation, with and without potential irrigation expansion, were considered. All configurations of water availability, policy decisions, and irrigation expansion options were fed into the $SWAMP_{SK}$ to obtain empirical probability distributions (risk) of system performance under considered scenarios of change. Based on the probabilistic representation of system performance under changing conditions (and hence the likelihood of system failure), the empirical distributions were used to quantify the individual and joint impacts of changing conditions on the system performance. Using this framework, it was demonstrated that optimal policies can change depending on flow conditions and the level of irrigation expansion. In the following section, the contributions and specific findings of these efforts are highlighted and discussed.

5.2 Research contributions and findings

5.2.1 Contributions and findings related to the integrated water resource system modeling in Saskatchewan

$SWAMP_{SK}$, introduced in Chapter 2, provides new developments that are represented as three sub-models. These developments were proposed for water allocation, irrigation demand and economic evaluation. First, the implemented water allocation algorithm can be used for a wide range of water resource systems models. Second, the irrigation demand was linked dynamically to the water allocation and the effects of two key sources of uncertainty, namely reference evapotranspiration and soil moisture accounting, were analyzed. Such analyses are necessary for places in which irrigation is a key water use. Finally, by estimating the annual economic net benefits of water allocation, a practical measure was provided to reveal economic trade-offs and competitions among water sectors. These three developments, applied within the System Dynamics approach, result in an efficient platform for planning and communicating the assessment results with various groups of stakeholders and can be simply transferred to similar case studies. From a broader perspective, Chapter 2 provided a strong support for the usefulness of integrated water resource systems models for understanding the functionality of complex water resource systems and the trade-offs among various water sectors. The developed $SWAMP_{SK}$ is a transparent model and therefore, can provide an efficient negotiation tool for multi-disciplinary group of stakeholders. This tool can be used to track the impacts of changing conditions on the system performance and to test the applicability of alternative policies.

More specifically considering the SaskRB in Saskatchewan, the performed analyses showed that coupling water allocation and irrigation demand models is important and can lead to more realistic estimation of irrigation demand at every time step. It has been shown that the estimated irrigation demand is sensitive to the selection of the reference evapotranspiration and soil moisture accounting models. Nonetheless, as the current irrigation demand is marginal compared to the normal annual water availability in Saskatchewan, the resulting differences in irrigation demand are rather small. It was also found that increase in irrigation level can increase the total economic benefit but with some cost of decreasing water availability in the system, which can indirectly affect the ecosystem of the SRD.

5.2.2. Contributions and findings related to the assessment of vulnerabilities in Saskatchewan under irrigation expansion and uncertain water availability

The analyses made in Chapter 3 illustrated the practical utility of fully bottom-up vulnerability assessment in understanding and visualizing hydro-economic trade-offs in the performance of water resource systems under changing conditions. The selected algorithm for streamflow reconstruction was also extensively tested in this chapter to highlight its strengths and weaknesses. It was found that when the reconstructed flows are linearly transferred to other locations, the spatial dependence in the regional streamflow regime is distorted. Such misrepresentation of the spatial dependence can particularly affect the quality of streamflow reconstruction during annual low and high flow conditions. The sensitivity of the analysis to alternative reconstruction pathways was also explored. Results show that estimated changes in system performance are relatively insensitive to the reconstruction pathway. For instance, the maximum relative difference in hydropower net benefit is about 5% under different reconstruction pathways.

More specifically and with respect to the considered case study, the results imply that hydropower production is more sensitive to changes in annual flow volume than changes in flow peak timing and/or increase in irrigation demand. Irrigation expansion can increase the average agricultural net benefit; however the results are highly dependent on water availability conditions. Therefore, irrigated agriculture might face loss in revenue under expansion and extremely dry flow conditions. In addition, it was found that the frequency of the peak flow in the SRD is more sensitive to changes in the incoming flows to the system rather than expanding irrigation. In fact, irrigation expansion can only affect the peak flow frequency of the SRD in extremely dry conditions. The results also showed that Saskatchewan can meet the inter-provincial commitment even under the driest flow conditions and the largest irrigation expansion considered. Further analysis showed that warming climate increases the irrigation demand; however the amount of this increment does not have a large effect on the water resource system due to sufficient water availability in the system. Overall, this study highlighted that the presented method is promising for evaluation of system performance under changing conditions. Therefore, the application of the analysis framework and its utility for decision analysis under changing conditions is recommended in other regions.

5.2.3. Contributions and findings related to the risk-based water resource management under changing water availability, policy and irrigation expansion

The proposed risk-based framework, presented in Chapter 4, enables quantification of variations in system performance corresponding to various changing conditions in a probabilistic manner. The framework has a methodological contribution towards improvement of current risk-based assessments from various aspects. For example, the main difference of the proposed framework from the available approaches is the fact that not only does it account for climate risks but also allows for explicit understanding of the extent of variations in the system performance as a result of multiple changing conditions. In particular, the proposed probabilistic framework provides an innovative way of understanding risk in system performance under changing conditions and allows improved decision making under uncertainty. In particular, it can be applied to understand how various combinations of changing factors can intensify or suppress the performance of water resource systems. This framework is quite generic and can be simply linked to any vulnerability assessment scheme (top-down or bottom-up) and be applied to other regions throughout the globe.

Considering the SaskRB-Saskatchewan case study, the risk-based framework provided important new insights into the variations in sectorial and provincial net benefit in the system as a result of changing water availability, reservoir operational policies and irrigation expansion. In brief, the results showed that the hydropower net benefit is more sensitive to changing flow conditions than expanding irrigation area under current policy in Saskatchewan. In addition, irrigated agriculture’s net benefit is only sensitive to the selection of policy options under expanded irrigation. Interestingly, alternative policies can both amplify or reduce the competition between productivity of irrigated agriculture and hydropower sectors, depending on the level of irrigation expansion and flow conditions. The results presented for the Provincial Net Benefit (PNB) indicated that under current policy, irrigation expansion can change the PNB quantiles from -9% to 18% depending on the flow conditions. In addition, it was showed that under current irrigation level, alternative policies are on par in terms of changing the PNB quantiles. However, as irrigation level increases, different policies present significantly divergent levels of change in PNB quantiles. It was also found that the joint impacts of changing water availability, policy, and irrigation expansion on the overall system performance are complex nonlinear functions of individual drivers.

5.3 Limitations and suggestions for further research

Chapters 2 to 4 presented new findings with respect to (1) complex causal relationships between various components of the SaskRB water resource system in Saskatchewan; (2) vulnerabilities in this system due to changes in natural and/or anthropogenic conditions; and (3) the effect of alternative policy decisions in suppressing and/or amplifying the vulnerabilities in system performance under changing conditions. Regardless of the developments made, there are certain limitations associated with the findings reported in this thesis. Below, these limitations are briefly summarized and directions for future developments are suggested.

The **SWAMP$_{SK}$ model** provides a holistic view on the functionality of the water resource system in the SaskRB in Saskatchewan and reveals the socio-economic and environmental trade-offs in the system; however, the understanding obtained can be further improved. One fundamental challenge with respect to the water resource models is the scale and the level of detail, with which the water availability, water demand and water allocation are represented. Water resource systems often include sectors that operate at different temporal scales. For example, hydropower operation requires decisions at hourly to daily scale, while irrigation demand should be characterized at daily to weekly scale and industrial demands can be calculated at monthly to yearly scale, mainly due to the operational needs and temporal variability in these demands. On one hand, if all processes are represented at a similar fine temporal scale, then the resulting system becomes too complex. On the other hand, if the temporal scale becomes too coarse, then the system behavior cannot be well evaluated, particularly under changing conditions. Major efforts are, therefore, required to construct integrated water resource models that can operate at multiple scales. Particularly, regarding the developed $SWAMP_{SK}$ model, it is suggested to estimate the irrigation and hydropower demand at a daily scale, and to operate the rest of the system on the considered weekly time resolution. In addition, further attempts are required to better represent environmental flow requirements in the region. Currently the environmental flow is represented as a constant flow rate, but it can be better described as a function of various driving factors. Such improvements are important, in particular for the SRD, where the livelihood of riparian and aquatic ecosystems cannot be represented by constant flow threshold. Furthermore, the economic evaluation sub-model of $SWAMP_{SK}$ can be further expanded to include more advanced economic factors such as opportunity costs of various water sectors. In addition, in our analyses it was assumed that costs and prices of production are fixed and not varying values. This assumption limits the scope of the evaluation component of the model, and should be relaxed by considering the effect of various factors including changes in water availability, technological improvement, and market on costs and benefits. From a broader perspective, it should be noted that operational policies and demand conditions were kept similar in the course of simulation, which is indeed not realistic. This assumption must be relaxed by incorporating gradual changes in water demand and incorporating adaptation in policy options, depending on the flow conditions and demand pressure. Finally, it should be noted that the current $SWAMP_{SK}$ does not incorporate sub-systems along the southern branch, such as Qu'Appelle diversion in the Province. Therefore, it is recommended to extend the spatial extent of $SWAMP_{SK}$ to provide a complete picture of the interconnected water resource systems in the region.

Vulnerability analysis, presented in Chapter 3, revealed the sensitivity of SaskRB-Saskatchewan to possible changes in the system. The proposed fully bottom-up approach by Nazemi et al. (2013) was used to generate flow conditions without using hydrological and climate models. While the concept and application of a fully bottom-up approach in system vulnerability assessment under changing flow conditions is generic, there are some specific limitations in the proposed flow reconstruction algorithm. For example, it assumes that changes in the streamflow regime can be represented only by changes in annual streamflow volume and annual peak flow timing. Accordingly, the impacts of other properties of streamflow such as interannual variability and duration of dry periods, which are prominent factors in managing water resources, are ignored. Thus, the streamflow reconstruction method needs to be improved and extended to include more diverse streamflow characteristics. In line with this, Borgomeo et al. (2015) recently proposed a fully bottom-up approach to synthetically generate streamflow realizations by considering various user-specified streamflow characteristics. Some other limitations in our analysis are related to maintaining the spatial dependencies between reconstructed streamflow series using linear correlation. More advanced methods should be further developed for improved reconstruction of spatially correlated flows. In addition, it is assumed that possibilities represented through the feasible ranges of change in streamflow regime are equally likely to happen in future. This assumption should be relaxed by using the results of top-down assessments, i.e. cascade of climate and hydrological model, to identify the chance of possible future conditions in light of the available projections.

The novel risk-based framework, proposed in Chapter 4, allows the quantification of risk in system performance without the necessity to deal with uncertainties associated with top-down assessment. However, it should be noted that top-down assessment can be used to weigh future conditions and identify the posterior risk profiles corresponding to the projected water availability conditions. In addition, in Chapter 4 only a limited number of policies were used to represent the long-term operation in the system. Further efforts are needed to systematically generate and use a wide range of policies to find the optimal options that perform well under changing water availability and irrigation expansion. This can provide a basis to find Best Management Practices under changing conditions. Finally, the notion of risk only presented for economic-based indices. It is suggested, therefore, to expand the analysis to evaluate the effects of changing conditions on non-economic performance measures as well.

Regardless of the noted limitations, the proposed risk-based framework in Chapter 4 provides an innovative of way of exploring risk in system performance under changing conditions. This framework can be used as a strong foundation for decision-making under uncertainty as it assists in choosing policies that can reduce risk in system performance under uncertain future conditions. Together with materials in Chapters 2 and 3, this thesis can be considered as an important step towards improving water resource management under deep uncertainty and effects associated with global change at watershed and regional scales.

5.4 References

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Appendix B – Supplementary materials for Chapter 2

Description: This section presents further information on the SaskRB in Saskatchewan. The properties of key reservoirs in SaskRB as well as the considered soil properties and crop types are presented in Table B-1 and B-2. Figure B-1 presents monthly crop coefficients used in the $SWAMP_{SK}$ to estimate crop evapotranspiration. Figure B-2 shows monthly extraterrestrial radiation ($MJm^{-2}d^{-1}$), mean air temperature (°C), difference between maximum and minimum air temperature (°C), precipitation (mm), slope of saturation vapor pressure-temperature curve ($KPa°C^{-1}$), actual vapor pressure (KPa), and wind speed at 2-m height (m/s) for the simulation period of 1970-2004.

Table B-1 Properties of main reservoirs in SaskRB in Saskatchewan

Reservoirs	Purpose	Construction year	Height (m)	Maximum capacity (MCM)
Lake Diefenbaker	Multi-purpose	1967	66	11311
Codette	Hydropower	1986	38	565
Tobin Lake	Hydropower	1963	32	3593

Table B- 2 Crop properties and soil type in Saskatchewan

Crop	Yield response factor over growing season	Growing season (month)	Soil type
Potato	1.1	5	Loam*
Grass	1.1	5	Loam
Barley silage	0.9	5	Loam
Alfalfa	1.15	5	Loam
Pea	1.15	3	Loam
Canola	0.95	5	Loam
Wheat	1.15	5	Loam

*Field capacity and wilting point of loam are 27 and 12 (v%), respectively.

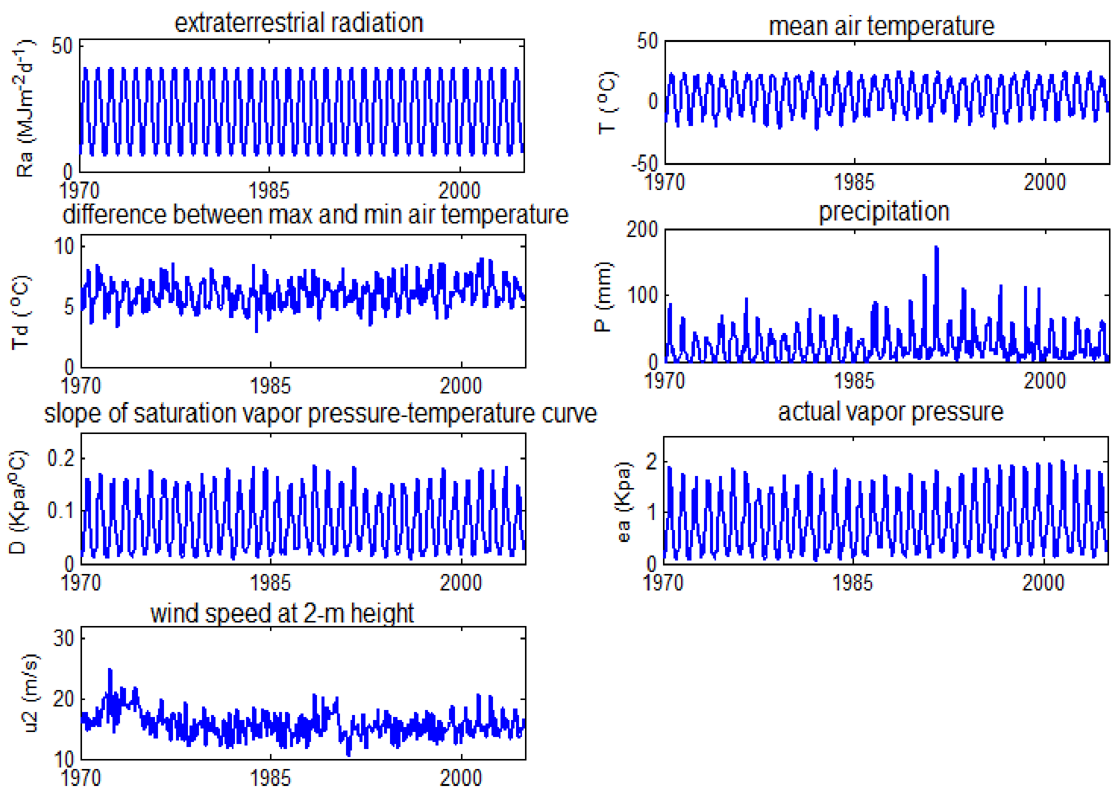

Figure B-1 Monthly variables used to calculate ET_0 for the period of 1970-2004

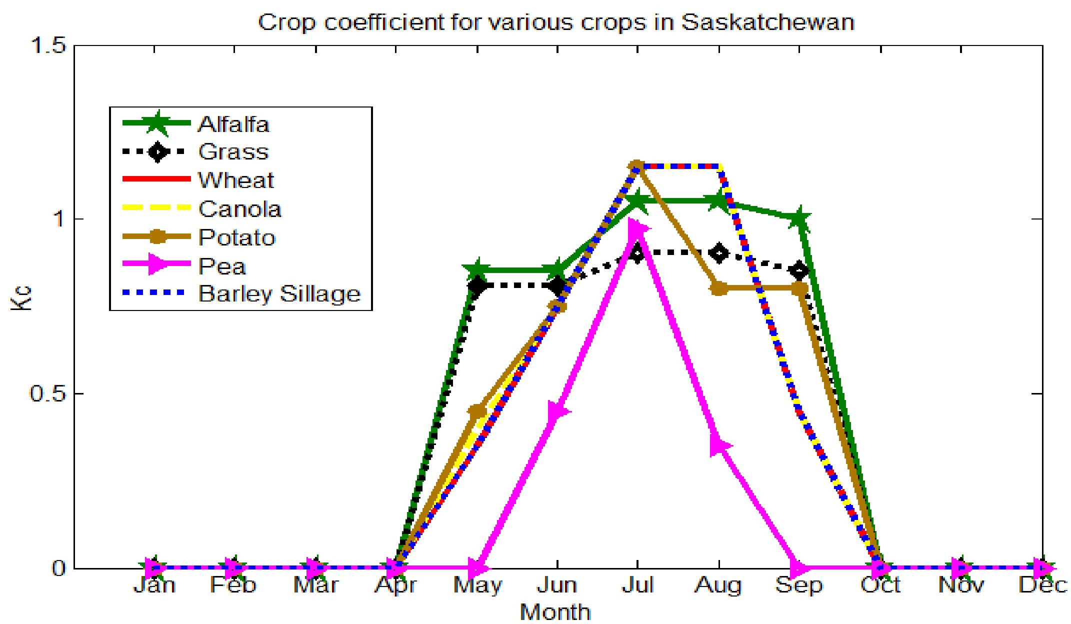

Figure B-2 Monthly crop coefficient (Kc) for various crops in Saskatchewan

Appendix C – Supplementary materials for Chapter 3

C.1 Reconstructed SSR and NSR flows under different scenarios of change

Figure C-1 compares the expected hydrograph for observed flows with the expected reconstructed hydrographs for different combinations of changes in timing of the peak and annual volume. Each panel corresponds to a specific cell. The upper and lower rows show the results for the SSR and NSR, respectively. The expected hydrographs for observed SSR and NSR flows are shown using solid lines in each row. The timing and volume of the reconstructed hydrographs (boxplots) adequately represent the selected changes in the timing and volume of the observed flow in both streams.

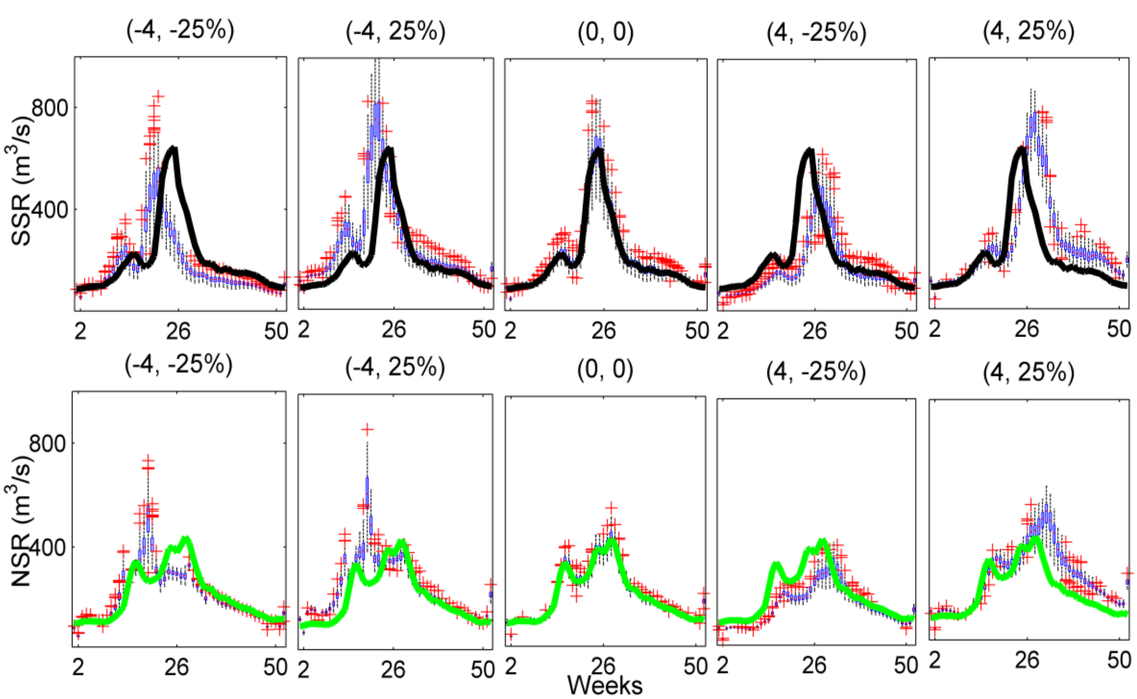

Figure C-1 Comparison between the expected and observed (solid lines) versus reconstructed (boxplots) flows for various flow regimes

C.2 Effect of water availability change and irrigation expansion on streamflow regime in the Saskatchewan River Delta

The effect of changes in upstream water availability and irrigation development on the SRD was also investigated in terms of the ensemble changes in the SR flow regime. For each realization, weekly maximum, median, and minimum SR flow during 31 years were found. The expected range of these SR flow statistics based on 200 realizations for each cell was then obtained. In Figure C-2, results are shown under three selected water availability conditions, i.e., (-4, -25%), (0, 0), and (4, 25%). The range of variability in the SR flow under maximum, median, and minimum values is presented from top to bottom in each panel. Comparing left and right panels show that there is little variation in the statistical characteristics of the SR streamflow with increasing irrigated area. As an example, in the upper, middle, and lower rows, the magnitudes of the largest SR flows in the S0 scenarios are about 52, 28, and 21 m^3/s higher than the largest SR flows in S4, respectively. Nonetheless, considering the panels in each column, changes in water availability conditions significantly affect the volume and peak timing of the SR flows. For instance, in the first column (S0 scenarios), the largest SR flow in (4, 25%) is about 130 and 303 m^3/s higher than the largest SR flows in the (0, 0) and (-4, -25%) cases, respectively.

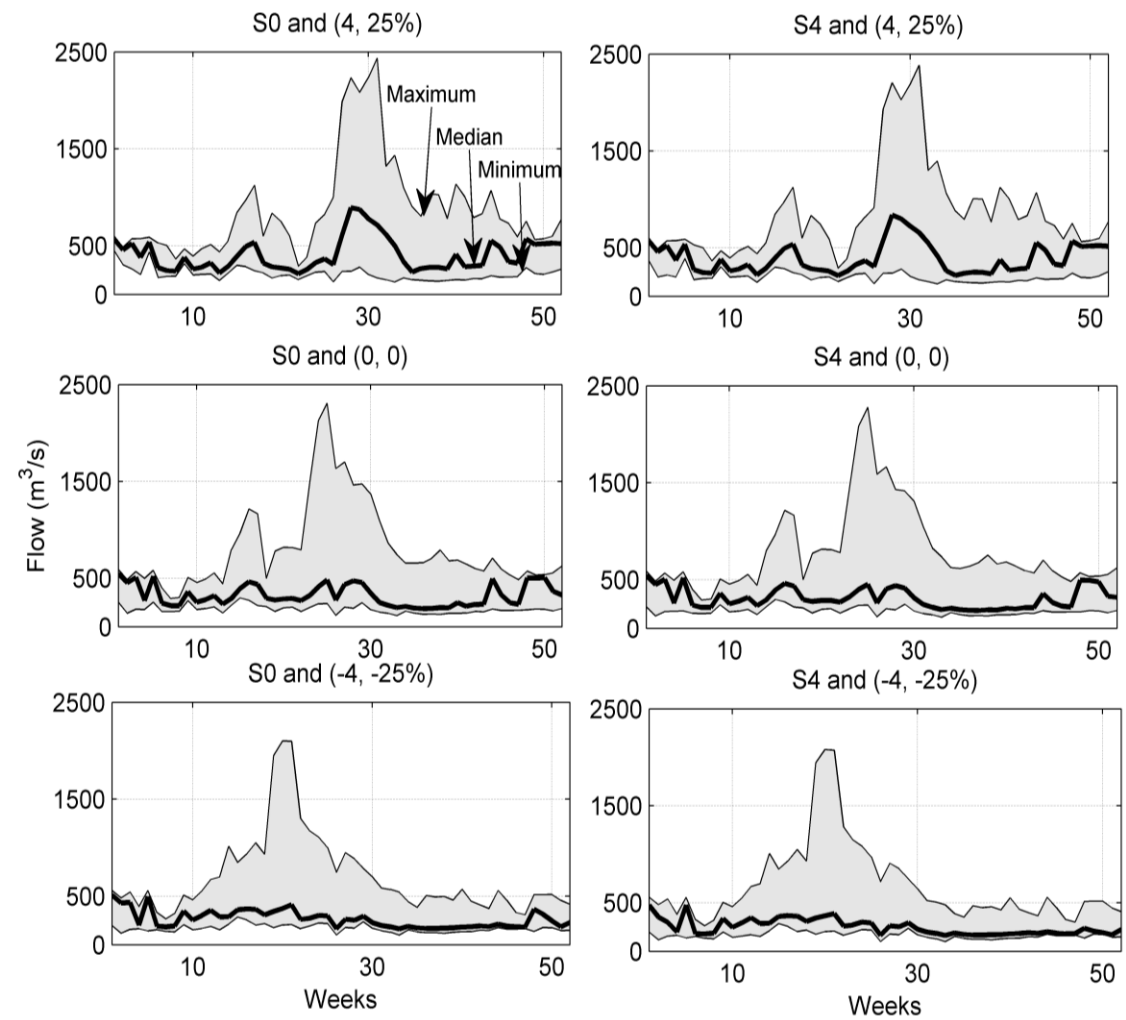

Figure C-2 SR flow statistics for changes in water availability conditions under (4, 25%), (0, 0), and (-4, -25%) for current (S0) and the largest irrigation development level (S4). Each panel includes the average of maximum, median, and minimum of the weekly SR for 200 realizations in each cell, respectively.

Appendix D – Supplementary materials for Chapter 4

D.1 Effect of changing water availability, policy, and irrigation expansion on hydropower net benefit

Variation in hydropower NBs under entire ensemble of changing water availability and policy conditions without and with irrigation expansion is shown in Figure D.1. This figure indicates that irrigation expansion does not significantly alter the ECDFs of hydropower NB under all considered changing water availability conditions.

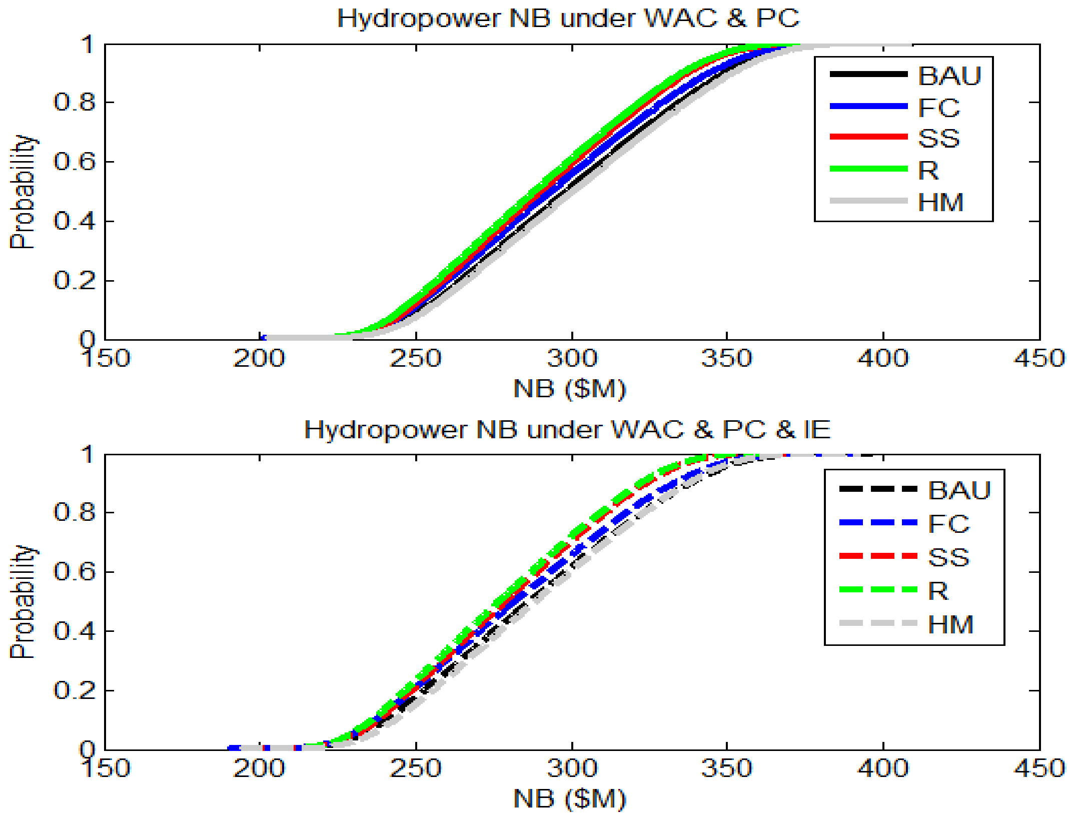

Figure D-1 Comparison between hydropower NBs under water availability change (WAC), policy change (PC), without and with irrigation expansion (IE)

D.2 Effect of changing policy, and irrigation expansion on Saskatchewan's non-economic management concerns

This section provides some information about the impacts of random variability, policy, and irrigation expansion on some non-economic provincial concerns. The management concerns and associated target performances are presented in Table D-1. For this assessment purpose, relative changes in the performance of alternative policy decisions under (0, 0) cell, without and with irrigation expansion were compared to a benchmark, which represents the results under (0, 0) cell, the BAU and current irrigation area (Table D-2).

Table D-1 Management concerns and targets in Saskatchewan's water resources system

Management concern	Service aspect	Location	Management target
Nesting habitats of Piping Plover, an endangered bird species	Environmental & ecological	Lake Diefenbaker	Lake Diefenbaker water level > 554.95 & <=555.35 on July 1st
Recreation activities	Socio-economic	Lake Diefenbaker	Lake Diefenbaker water level > 555 and <555.6 on July 1st
Flooding in the Berry Barn area, a Saskatchewan tourist attraction with valuable crops	Socio-economic	Moon Lake	SSR flow close to Saskatoon < 900 m^3/s during May 1-October 30
Flooding in the SRD	Socio-economic & environmental	Saskatchewan River Delta	SR flow < 2500 m^3/s

Table D-2 Comparison between relative decline/incline in performance levels associated with different operational policies and irrigation levels for key provincial concerns with respect to the values in the BAU policy under (0, 0)

Policy/Provincial concerns		Piping plover Protection	Recreation incline	Flood Reduction in the SRD	Flood reduction in Moon Lake
Current irrigation area	BAU	--	--	--	--
	FC	-84%	-60%	100%	34%
	SS	-29%	88%	-13%	-122%
	R	-56%	125%	-13%	-111%
	HM	-48%	-8%	8%	7%
Expanded irrigation area	BAU	-11%	20%	18%	16%
	FC	-86%	-60%	100%	34%
	SS	-50%	88%	-8%	-94%
	R	-32%	125%	-8%	-85%
	HM	-50%	-13%	25%	12%

The results indicate that under all policy conditions, there is an increased threat of submerging Piping Plover nesting habitats. FC and BAU policies result in the largest and smallest harm on protecting nesting habitats of Piping Plover. As expected, the recreation policy (R) under current and expanded irrigation increases the recreation feasibility in reservoir by more than 125%. FC reduces the recreation chance by 60%, which is logical as the objective of this scenario is to empty reservoir water level as much as possible to control spring and summer floods. SS increases recreation as this scenario attempts to increase water level in reservoir. HM drops recreation possibility by about 10% under both irrigation scenarios. All polices are consistent (positive/negative) in reducing/increasing the level of performance associated with flooding in the Moon Lake and SRD. FC is the most successful scenario in reducing the flood risk in the SRD. HM policy under expanded irrigation is also efficient in reducing floods in the SRD and the Moon Lake (Berry Barn). As both R and SS policies maintain high reservoir water level, they cause the largest chance of flooding in the region. Furthermore, it is apparent that all policies under irrigation expansion reduce risk of flooding compared to current irrigation scenario as irrigated agriculture consumes available water in the system and therefore reduces the flood risk.