AN INTEGRATED WATER RESOURCES MANAGEMENT FRAMEWORK FOR ROBUST DECISION-MAKING IN A TRANSBOUNDARY RIVER BASIN: AN INTER-REGIONAL HYDRO-ECONOMIC APPROACH

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By

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Abstract

Allocating limited amounts of freshwater among competing uses is challenging, particularly in transboundary river basins and under the impact of climate change and increasing demand for water associated with population growth and economic development. This calls for decision support tools that inform decision-makers about the consequences of their water management strategies and the impacts of changes in water availability due to climate change and socio-economic development. Hydro-economic models have proven to be promising for helping understand these impacts from an economic perspective. These models need to be integrated and capture both features of the water system and the economic interdependencies to be effective in multi-sectoral and multi-regional river basin contexts. Many of the hydro-economic models, however, adhere to either hydrological or administrative boundaries due to the limited availability of hydrological and economic data at relevant temporal and spatial scales. These models usually consist of a detailed representation of either the water or the economic system and a simplified representation of the other system. This is mainly because an integrated model including a detailed representation of both water and economic systems is extremely data-demanding and challenging to develop due to the different resolutions of datasets associated with these models.

This dissertation attempts to address this gap by developing an integrated hydro-economic model that encompasses an entire transboundary river basin and consists of detailed water and economic components to inform decision-making about sustainable and robust water allocation. This is accomplished through these main steps: (1) developing an Inter-regional Supply-side Input-Output (ISIO) model incorporating water supply data for the transboundary Saskatchewan River Basin; (2) testing the temporal transferability of the ISIO model for different years in predicting the economic response of the river basin to changes in water availability under different climatic conditions; (3) coupling the ISIO model with a node-link water resources system model (MODSIM) to create an integrated hydro-economic model; (4) applying this integrated hydro-economic model to identify the sectoral and regional vulnerabilities of the river basin to changes in water supply; and (5) comparing the economic outcomes of the integrated hydro-economic model with those coming from an engineering model (the MODSIM model linked to a crop yield function) and the ISIO model.

The contribution of this dissertation is developing an integrated hydro-economic model that couples detailed water resources system and inter-regional supply-side input-output models to identify sectoral and regional vulnerabilities of transboundary river basins to changes in water availability. The findings of this research have advanced our understanding of the cross-sectoral and inter-regional distribution of economic impacts of water allocation strategies and other drivers, including climate change and socio-economic development. This research also investigates, for the first time, the performance of supply-side input-output models that include water under different climatic conditions and over several years. This dissertation serves as an example for future integrated hydro-economic modelling attempts, particularly for informing decision-making about sustainable and robust water allocation in multi-sectoral and multi-regional river basins.

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I would like to extend my sincere gratitude to my supervisors, Dr. Saman Razavi and Professor Roy Brouwer, for their support, stimulating ideas, encouragement, and constructive advice throughout this journey. This research would not have been possible without their support and contribution. I also want to offer my special thanks to my advisory committee members, Professor Howard Wheater, Dr. Mohamed Elshamy, Dr. Patrick Lloyd-Smith, Dr. James Robson, and Dr. Lori Bradford for their invaluable and insightful feedback and comments. Finally, I would like to thank my family, especially my mother, for the unconditional love and support in my whole life and in particular during these past four years.

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Chapter 1

Introduction

1.1. Background and Motivation

The limited amount of available freshwater makes its allocation among competing uses challenging due to the trade-offs involved. Examples of such trade-offs are the lost opportunities of water use in one sector (e.g., residential water supply, industrial water use) when using them in another sector (e.g., irrigation). These trade-offs become even more complex when considering the impact of drivers such as climate change and socio-economic development in river basins shared among multiple jurisdictions. Under evolving climate and socio-economic conditions, predicting the available amount of water and demand for water becomes even more challenging due to uncertainties associated with coupled water and human systems (New and Hulme, 2000; Haasnoot and Middelkoop, 2012). This calls for modelling approaches that help us to understand water resources and demand systems from multi-disciplinary perspectives, combining different knowledge systems to capture the complexities and trade-offs involved. These perspectives, including hydrological, environmental, economic, social, and political should be incorporated into the modelling approaches to create integrated and interdisciplinary models that support decision-making on water management strategies (Croke et al., 2007; Cai, 2008; Ward, 2009; Wheater and Gober, 2013; Lund, 2015; Vogel et al., 2015; Loucks and van Beek, 2017; Badham et al., 2019). This helps identify vulnerabilities of river basins from different perspectives. Vulnerability is defined here as the tendency "to be adversely affected", including "sensitivity" to and "lack of ability to adapt" to future conditions, e.g., climate change, policy interventions, and socio-economic developments (IPCC, 2020).

Among these perspectives, the economy as "the study of the allocation of scarce resources" (Russell and Wilkinson, 1979) among unlimited wants plays a crucial role in informing decisions about water allocation among competing uses. Economic principles have been included in water management since the 1960s (Lund et al., 2006; Harou et al., 2009) and are at the heart of hydro-economic models (Heinz et al., 2007; Brouwer and Hofkes, 2008; Harou et al., 2009). By integrating water-related and economic components, hydro-economic models have been applied in water resources management to study several water-related issues, including water quality (e.g., Duarte Pac and Sanchez-Choliz, 1998; Brouwer et al., 2008; Dellink et al., 2011; Liu et al., 2019) and water quantity (e.g., Cai et al., 2003; Velázquez, 2006; Harou et al., 2010; Ward, 2014; Kahsay et al., 2017; Ridoutt et al., 2018) issues.

Hydro-economic models have been developed using different approaches. One modelling approach is linking a detailed water-related model (e.g., a node-link water management model, or a detailed environmental water quality model, etc.) to an economic component with a partial equilibrium approach that captures the economic impacts on one sector or one part of the economy (e.g., Cai et al., 2003; Cai and Wang, 2006; Ahrends et al., 2008; Harou et al., 2010; Ben-Gal et al., 2013; Blanco-Gutiérrez et al., 2013; Arjoon et al., 2014; Ward, 2014; Esteve et al., 2015; Kahil et al., 2016; Foster et al., 2017; Jalilov et al., 2018; Amjath-Babu et al., 2019; Ward et al., 2019; Li et al., 2020; Meng et al., 2020). Another approach is developing macroeconomic models, such as general equilibrium (e.g., Gómez et al., 2004; Berrittella et al., 2007; Calzadilla et al., 2010; Rivers and Groves, 2013; Luckmann et al., 2014; Levin-Koopman et al., 2015; Kahsay et al., 2017; Levin-Koopman et al., 2017; Teotónio et al., 2020) or input-output (e.g., Duarte et al., 2002; Velázquez, 2006; González, 2011; Cazcarro et al., 2013; Pérez Blanco and Thaler, 2014; Bogra et al., 2016; Ridoutt et al., 2018; Almazán-Gómez et al., 2019; Garcia-Hernandez and Brouwer, 2020) models that embed a set of water-related data, such as water use or water pollution data. There is also a limited number of studies that couple a detailed water-related model with a general equilibrium or an input-output model (e.g., Jonkman et al., 2008; Dellink et al., 2011; Kahsay et al., 2019; Knowling et al., 2020; Tanoue et al., 2020). The considerably lower number of these studies attempting to develop integrated hydro-economic models compared to other modelling approaches can be attributed to the extremely data-demanding nature of these models and the integration challenges due to different spatial and temporal resolutions of hydrological and economic components of the model (Brouwer et al., 2005; Brouwer and Hofkes, 2008; Cai, 2008).

In order to be useful as a practical and operational decision support tool in a multi-sectoral and multi-regional river basin, hydro-economic models need to be able to appropriately capture and represent (1) the different regions or sub-basins and their connectivity across the entire river basin and (2) the relevant hydrological (water management) and economic features characterizing the river basin and their interactions. The former enables us to evaluate the impacts of different water management strategies in one part of the river basin on the other parts, taking into account inter-regional relationships in river basins. By focusing only on one part of a multi-regional river basin, we are likely to overlook the impacts of the water management strategies on water and economic systems in other parts of the basin. The latter allows us to identify the distribution of consequences of water management decisions or exogenous drivers affecting the availability of water resources in a river basin, such as climate change or socio-economic development, across different sectors.

Despite the role that such integrated hydro-economic models can play to support decision-making, particularly in multi-jurisdictional river basins, only a limited number of published studies have attempted to develop and apply these integrated hydro-economic models with such characteristics to inform water allocation among competing uses in a transboundary river basin context (e.g., Kahsay et al., 2019). Many, if not most of the previous hydro-economic models adhere to either administrative or hydrological boundaries (e.g., Velázquez, 2006; González, 2011; Rivers and Groves, 2013; Esteve et al., 2015; Ridoutt et al., 2018). On one hand, economic data are typically released at administrative levels, e.g., national or provincial levels. On the other hand, water use and hydrological data are usually available at the catchment scale. In a multi-regional river basin, therefore, hydro-economic models should reconcile administrative and hydrological boundaries to connect the two datasets and generate results that could be used at scales relevant to water allocation decisions.

Previous models that applied a partial equilibrium approach and focused mainly on one or a limited number of economic sectors while ignoring the rest of the economy typically do not capture cross-sectoral connectedness, and hence often only estimate the direct economic impacts, or use multipliers to assess possible indirect effects. Direct economic impacts are limited to the impacts of an exogenous change on the parts of the economy directly affected by that change (Kulshreshtha and Grant, 2003). For example, if the water supply to one sector, e.g., irrigation, is reduced due to the impact of climate change, the production of this sector decreases consequently. However, as economic sectors hardly ever function in isolation, this reduction in the production of one sector (here irrigation) propagates to the rest of the economy through the purchases of other sectors from the directly affected sector. These inter-sectoral (and inter-regional) transactions indirectly affect the economy (Kulshreshtha and Grant, 2003).

Several hydro-economic models have been applied to identify vulnerabilities by evaluating the economic impacts of climate change or other drivers (e.g., Wang et al., 2008; Ali and Klein, 2014; Esteve et al., 2015; Kahil et al., 2015; Hassanzade et al., 2016; Kahsay et al., 2017; Kahsay et al., 2019; Maneta et al., 2020; Tanoue et al., 2020). Only a limited number of these studies, however, used a fully integrated modelling approach (e.g., Kahsay et al., 2019; Tanoue et al., 2020) from which hardly any, to the best of the author's knowledge, have been used to inform robust decision-making about water allocation strategies in transboundary river basins. Robust decision-making is defined here as identifying strategies that reduce vulnerabilities in the face of future conditions and perform well under a wide range of plausible scenarios (Lempert and Groves, 2010; Herman et al., 2014; Bhave et al., 2016).

These gaps in the literature motivate the present dissertation to set the main objective as to develop an integrated, basin-wide hydro-economic model accounting for both direct and indirect economic impacts to identify sectoral and regional vulnerabilities (i.e., the sensitivity of different sectors or regions to the adverse impact of future conditions) and to support robust decision making in a transboundary river basin, as outlined in the next section.

1.2. Sustainability in Water Resources Management

The circumstances described in the previous section, where tradeoffs are inevitable due to limited amounts of available freshwater and increasing conflicting demands, call for moving towards sustainable allocation of our water resources. Discussions around sustainable development of natural resources, including water, have been triggered by increasing international concerns regarding natural resources management and preservation since the 20th century (Drexhage and Murphy, 2010). According to one of the most popular definitions, sustainable development needs to satisfy the needs of the current and future generations while preserving the natural resources (WCED, 1987). Particularly focused on water resources, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the American Society of Civil Engineers (ASCE) define sustainably managed water resource systems as water systems that satisfy the current and future needs of the society while preserving their environmental, ecological, and hydrological integrity (ASCE, 1998; UNESCO, 1999).

The "2030 Agenda for Sustainable Development" of the United Nations consisting of 17 Sustainable Development Goals (SDGs) (Figure 1.1) constitutes one of the most recent international guidelines towards sustainable development. Goal 12 of this agenda, namely "Responsible Consumption and Production", aims to "*achieve the sustainable management and efficient use of natural resources by 2030*" (United Nations, 2015) and directly addresses sustainable water resources management. Meanwhile, sustainable use of natural resources, particularly water resources, would be required to achieve some of the other SDGs, such as "No Poverty", "Zero Hunger", and "Clean Water and Sanitation".

To sustainably manage and allocate limited water resources, we need to study the consequences of alternative water allocation strategies from different perspectives. One of the most relevant perspectives here is the economic perspective as this study deals with allocating scarce water resources. This further motivates me to incorporate economy in water management frameworks in the present Ph.D. research.

Figure 1.1. Sustainable Development Goals (Retrieved from https://healthsciences.usask.ca/news-and-announcements/announcements/2020/sept-sdg-spotlight-all-goals-2020.php)

1.3. Objective and Research Questions

The overarching objective of this research is to develop an integrated hydro-economic model for a transboundary river basin to inform decision-making on sustainable and robust water management. Through this objective, the present dissertation aims to address the following key research questions:

1. How can water consumption and economic production be coupled in an integrated hydro-economic model describing the economy of a transboundary river basin?
2. How does the economy of a transboundary river basin respond to changes in water supply due to climate and/or policy changes?
3. How reliable are Supply-side Input-Output models in predicting economic production in a transboundary river basin over time when facing changes in water availability under different climatic conditions?
4. How can we capture sectoral and regional vulnerabilities to water scarcity across a transboundary river basin?
5. What is the relevance of cross-sectoral interconnectedness and inter-regional linkages in evaluating the economic impacts of changes in water availability in a transboundary river basin context?
6. How do predicted economic impacts under water supply changes differ when comparing the results from an engineering-based hydro-economic model, with the Supply-side IO model and an integrated hydro-economic model?

To achieve the above objective and address these questions, this research was conducted in the following main steps: (1) developing an Inter-regional Supply-side Input-Output (ISIO) model incorporating water supply data for a transboundary river basin; (2) testing the temporal reliability of the ISIO model for different years in predicting the economic response of a river basin to changes in water availability under different climatic conditions; (3) coupling the ISIO model with the available water resources system model (developed in MODSIM-DSS) to create an integrated hydro-economic model; (4) applying this integrated hydro-economic model to identify the sectoral and regional vulnerabilities of a river basin to changes in water supply; and (5) comparing the economic outcomes of the integrated hydro-economic model with those coming from the engineering-based model and the ISIO model.

1.4. Dissertation Outline

This dissertation includes four papers that address the above key research questions taking one or more of the main steps outlined in the previous section. These papers are presented in Chapters 2 to 5. Minor changes were made in each chapter to make the paper consistent with the body of the dissertation and avoid unnecessary repetitions. All references are presented at the end of the dissertation. Figure 1.2 shows how the different pieces of this research come together to achieve the overarching objective. The four contributions, presented in four manuscripts, and seven research questions of this study are mapped in this figure.

Chapter 2 (manuscript 1) presents the methodology of developing an Inter-regional Supply-side Input-Output (ISIO) model incorporating water supply data for the transboundary Saskatchewan River Basin (SaskRB) in Western Canada. The ISIO model is an analytical economic framework to study the impacts of changes in sectoral inputs on the gross output through the flow of goods and services among different economic sectors. This chapter also illustrates the application of this model in evaluating the economic impacts of water supply restrictions due to climate and policy changes using two hypothetical scenarios. The first two research questions are addressed in this first chapter (yellow box).

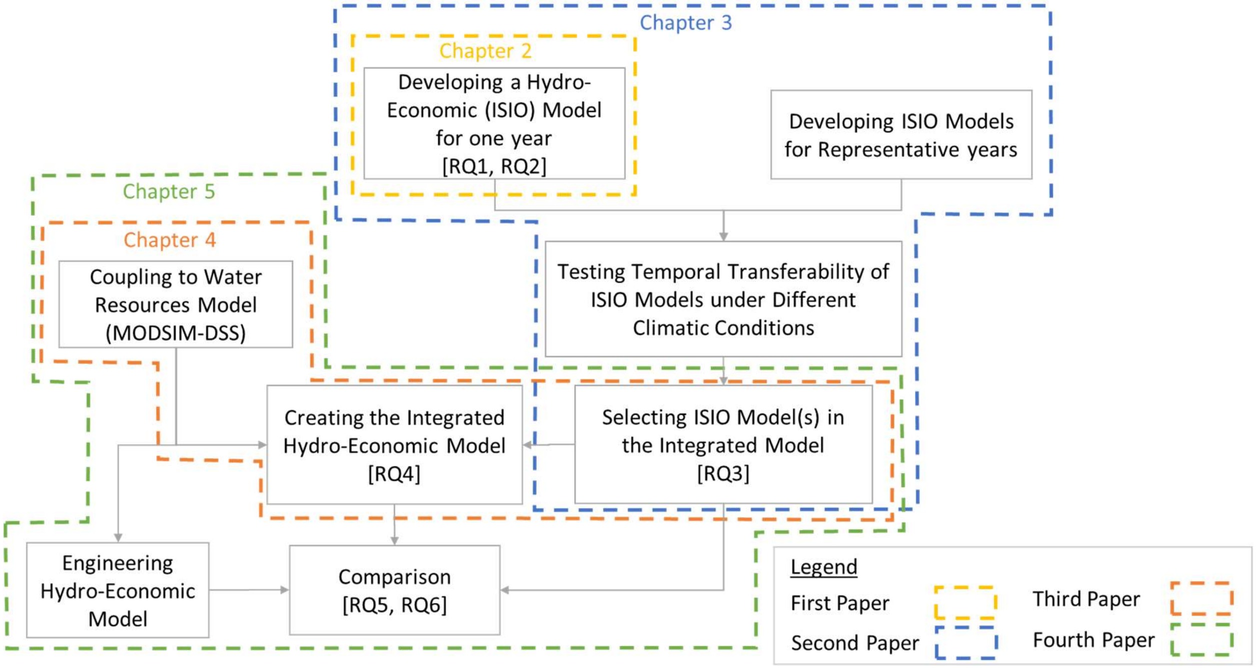

Figure 1.2. A diagram showing how the different pieces come together to create an integrated hydro-economic framework for water allocation. Numbers in brackets refer to research questions.

Chapter 3 (manuscript 2) investigates the temporal reliability of the ISIO models under climatic conditions different from that of the model's base year. This was implemented by developing ISIO models for four different years with different climate conditions, namely wet or dry climate conditions. Research question 3 is addressed in this chapter (dark blue box).

Chapter 4 (manuscript 3) presents the development of an integrated hydro-economic model and its application to support sustainable and robust decision making by identifying sectoral and regional vulnerabilities under climate change and socio-economic development. Research question 4 is addressed in this chapter where the ISIO model for the SaskRB is coupled with a water resources system model developed for this river basin in MODSIM-DSS (a node-link modelling program for river basin simulation) to create an integrated hydro-economic model. The integrated model is then applied to identify the economic responses by assessing the sensitivity of the SaskRB economy to changes in sectoral/regional water supply (orange box).

Chapter 5 (manuscript 4) examines the applicability and relevance of the integrated hydro-economic model in multi-sectoral and multi-regional river basin decision making by comparing the performance of this model to the performance of the ISIO model as a standalone model and an engineering-based model under climate change and socio-economic development scenarios. The last two research questions are addressed in this chapter. In this chapter, an engineering-based hydro-economic model is developed, where the water resources system model (MODSIM) is linked to a crop yield function that estimates the economic value of the change in production as a result of a change in water availability by multiplying the change in production by the average market price for the irrigated crop involved. The performance of this model in evaluating the economic impacts is then compared with those of the integrated model and the ISIO model without being coupled with MODSIM (green box).

Finally, Chapter 6 brings together the findings of the different steps of this research, presents the concluding remarks, and recommends directions for future research.

Chapter 2

The Economic Impacts of Water Supply Restrictions due to Climate and Policy Change: A Transboundary River Basin Supply-Side Input-Output Analysis

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Abstract

Finding sustainable pathways to efficiently allocate limited available water resources among increasingly competing water uses has become crucial due to climate-change-induced water shortages and increasing water demand. This has led to an urgent need for the inclusion of economic principles, models, and methods in water resources management. Although several studies have developed macro-economic models to evaluate the economic impacts of alternative water allocation strategies, many if not most ignore the hydrological boundaries of transboundary river basins. Furthermore, of those using input-output (IO) models, only a handful have applied supply-side IO models. In this chapter, we present one of the first attempts to develop an inter-regional, supply-side IO modelling framework for a multi-jurisdictional, transboundary river basin to assess the direct and indirect economic impacts of water supply restrictions due to climate and policy change. Applying this framework to the Saskatchewan River Basin in Canada encompassing three provinces, we investigate the economic impacts of two different water supply restriction scenarios on the entire river basin and its sub-basins individually. We find that in the face of climate-change-induced water shortage, economic losses can be reduced by almost 50%

by adopting appropriate management practices, including prioritization of water allocation, using alternative water sources, and water re-use technologies.

2.1. Introduction

The overexploitation of water resources and the degradation of their quality by human-driven activities have reduced the amount of available water in many regions around the world. This situation is expected to be intensified by climate change and increasing demand for water associated with population growth and economic development. Under such circumstances, allocating limited water resources in an efficient manner among competing water users becomes more and more critical (Renzetti and Dupont, 2017), particularly in transboundary river basins that are operated by different authorities. One way to allocate water more efficiently is to include economic principles and methods in water allocation and management practices (Harou et al., 2009). The need to consider water as an economic good in water management was acknowledged by the United Nations in its 1992 Dublin statement (U.N., 1992).

Several researchers have used economic modelling approaches to study either water quality changes caused by human activities (e.g., Duarte Pac and Sánchez Chóliz, 1998; Brouwer et al., 2008; Dellink et al., 2011) or human-induced water quantity changes (e.g., Cai et al., 2003; Velázquez, 2006; Harou et al., 2010; Ward, 2014; Kahsay et al., 2017; Ridoutt et al., 2018). While some of the studies investigating water quantity changes have applied combinations of hydrological simulation and economic optimization methods to identify the most promising sectoral water management practices based on economic parameters (e.g., Bielsa and Duarte, 2001; Cai et al., 2003; Jenkins et al., 2004; Booker et al., 2005; Medellín-Azuara et al., 2007; Harou et al., 2010; Blanco-Gutiérrez et al., 2013; Razavi et al., 2013; Asadzadeh et al., 2014; Graveline et al., 2014; Ward, 2014; Esteve et al., 2015; Bekchanov et al., 2016; Kim and Kaluarachchi, 2016; Amjath-Babua et al., 2019), only a number of these studies have used macro-economic models to evaluate the direct and indirect economic impacts of water management policies on the economy as a whole (e.g., Kulshreshtha and Grant, 2003; Velázquez, 2006; Guan and Hubacek, 2008; Calzadilla et al., 2010; González, 2011; Kahsay et al., 2017; Levin-Koopman et al., 2017).

One of these macro-economic models is the Input-Output (IO) framework originally developed by Leontief (1936), and later extended to account for environmental parameters, such as pollution caused by economic activities (Leontief, 1970). This framework has been used in water management studies mainly to estimate sectoral water consumptions in response to a change in final demand for water-dependent goods and services (e.g., Duarte et al., 2002; Velázquez, 2006; Cazcarro et al., 2013; Ridoutt et al., 2018). This IO framework was modified to accommodate limited resources, such as water, and the supply-side IO model was proposed to relate changes in sectoral inputs to sectoral production (Ghosh, 1958; Miller and Blair, 2009). The supply-side IO model has however been used in only a few studies to evaluate the economic impacts of water allocation and supply policies (e.g., Yoo and Yang, 1999; González, 2011; Bogra et al., 2016).

A critical step in including water in an economic model, either in physical units (e.g., Bogra et al., 2016), monetary units (e.g., Velázquez, 2006) or a combination thereof (e.g., water productivity as in Pérez Blanco and Thaler, 2014), is selecting the relevant spatial scale at which not only hydrological and economic data are available, but also modelling results could be used for water allocation decisions. This step is challenging due to the differences in spatial resolution of hydrological and economic data (e.g., Brouwer et al., 2005; Brouwer and Hofkes, 2008; Cai, 2008). Water extraction and use data are, for example, usually available at river-basin or sub-basin scale, whereas economic data are typically published at administrative scales such as a province, county, or country as a whole. The river basin or catchment is often the most appropriate study unit from the viewpoint of hydrology and water resources management and planning (Loucks and van Beek, 2005), while economic market data may better fit administrative boundaries.

Based on their spatial scales, existing IO studies that include water can be categorized into single and multi-region studies. Single region studies focus on one river basin (e.g., White et al., 2015) or one administrative unit (e.g., Velázquez, 2006; González, 2011), while multi-region studies consider several river basins (e.g., Ewing et al., 2012; Lutter et al., 2016), hydro-economic regions (e.g., López-Morales and Duchin, 2015), or a study region (like an irrigation district or a country) and the rest of the world (e.g., Kulshreshtha and Grant, 2003; Ridoutt et al., 2018).

Although these IO studies have contributed significantly to the advancement of hydro-economic modelling, hardly any have evaluated the economic impacts on interconnected hydrological units, i.e., sub-basins of a larger transboundary river basin. To fill this gap in the literature, this chapter aims to develop an inter-regional supply-side IO model that enables us to assess the direct and indirect economic impacts of various water supply restrictions under climate change and alternative water policies in a multi-jurisdictional river basin. This is one of the very first attempts to develop such a model that encompasses not only each of the provinces that share the river basin, but also the sub-basins and the entire river basin. To this end, hydrological and administrative boundaries are reconciled, and trade flows are identified and quantified between study units (i.e., sub-basins) to build relevant interconnections. Developing such a model is challenging due to limited data availability, and data sources are typically not compatible across different jurisdictions.

We apply this hydro-economic modelling approach to the Saskatchewan River Basin in Canada, a large, multi-jurisdictional river basin where water has been allocated traditionally through licenses on a “first-in-time, first-in-right” basis (Brooymans, 2011). From the three provinces sharing this river basin, Saskatchewan is the only one that has moved away from that basis in the 1980's (SWSA, 2012) to the current licensing system administered by the Saskatchewan Water Security Agency based on terms and conditions, which are not necessarily based on economic criteria, and for a specific duration only (instead of in perpetuity) (Government of Saskatchewan, 2018). The limited number of studies that have focused on IO modelling of this river basin (e.g., Martz et al., 2007; Paterson Earth & Water Consulting, 2015; Brown, 2017) have primarily investigated the economic impacts of climate change and irrigation development on either one sub-basin (e.g., the South Saskatchewan River Sub-basin) or one province (e.g., a part of the river basin in Alberta Province). These existing studies considering only a part of the Saskatchewan River Basin or adhering to administrative boundaries, fail to recognize that the basin is an integrated and interconnected system, from both hydrological and economic points of view, and disable any evaluation of the impacts of water allocation strategies and management practices in one part on other parts of the river basin. Therefore, the results of this chapter provide unprecedented insights into the hydro-economic interactions of this complex river basin, under alternative water policy scenarios.

2.2. Methodology: An Inter-Regional Supply-side Input-Output Model Including Water

2.2.1. Input-Output Modelling

An IO analysis is an analytical framework to study the interdependence of industries in an economy using the flow of goods and services among them in a certain period of time, usually a year (Leontief, 1936). This framework uses a set of linear equations to relate each sector's production (outputs) and the goods it consumes from other sectors (inputs). Considering an *n*-sector economy, the distribution of sector i's products to other sectors and end-users can be formulated as follows:

$$x_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{2.1}$$

where x_i is the total production of sector i, z_{ij} represents the purchase of all sectors j (including sector i) from sector i's products, and f_i is total final demand for the products of sector i , which is used by end-users including households, government, private investments, and exports. In matrix notation, Eq. (2.1) can be presented as:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{f} \tag{2.2}$$

where $\mathbf{i}$ is a summation vector (a column vector of ones). To indicate the relationship between inter-industry sales from i to j and the total production of sector j, let $a_{ij} = \frac{z_{ij}}{x_j}$, in which a_{ij} is commonly referred to as a "technical coefficient". The matrix of technical coefficients for an economy with *n* sectors can be written as $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, in which $\hat{\mathbf{x}}^{-1}$ is the inverse of a diagonal matrix with the elements of sectoral outputs along the main diagonal and zeros elsewhere[1]. Substituting $\mathbf{Z} = \mathbf{A}\hat{\mathbf{x}}$ into Eq. (2.2), we can rewrite this equation as $\mathbf{x} = \mathbf{Ax} + \mathbf{f}$ or $(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{f}$, in which $\mathbf{I}$ is an $n \times n$ identity matrix with ones on the main diagonal and zeros elsewhere. This equation can then be rearranged as follows:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{2.3}$$

---

[1] In this chapter, we use bold uppercase letters to represent matrices, bold lowercase letters to indicate vectors, (^) for the diagonal matrix, ($^{-1}$) to indicate the inverse matrix, and (^{T}) to transpose a matrix.

$(\mathbf{I}-\mathbf{A})^{-1}$ is known as *the Leontief inverse* (or *input inverse*) and indicates the total requirements (direct and indirect) of the sectors to produce one monetary unit of final demand (Miller and Blair, 2009).

Unlike the regular symmetric IO tables, in the *commodity-by-industry* IO tables more than one commodity can be produced by each sector. The Canadian System of Macroeconomic Accounts has used commodity-by-industry IO tables since the early 1960s (Statistics Canada, 1985). This framework consists of two main commodity-by-industry matrices, namely the *Supply* ($\mathbf{V}$) and *Use* ($\mathbf{U}$) matrices. The supply matrix represents the value of outputs of commodities produced by industries, whereas the use matrix represents the value of inputs (from commodities) that industries consume.

To create the Leontief equation for the commodity-by-industry IO system, total industry output and total commodity output are extracted from the supply matrix ($\mathbf{V}$). The column sums of the supply matrix show the total output of industries $\mathbf{x}=(\mathbf{i}^T)\mathbf{V}$, and the row sums of this matrix show the total output of commodities ($\boldsymbol{q}=\mathbf{Vi}$).

Let's define $\mathbf{T}=\mathbf{U}\hat{\mathbf{x}}^{-1}$, where matrix $\mathbf{T}$ consists of elements t_{ij}, each denoting the value of inputs of commodity i per one dollar's worth of industry j's output, and let $\mathbf{D}=\mathbf{V}\hat{\mathbf{q}}^{-1}$, where matrix $\mathbf{D}$ consists of elements d_{ij} representing the fraction of the total output of commodity i produced by industry j. $\mathbf{D}$ is known as the market shares matrix. By moving $\hat{\mathbf{q}}^{-1}$ to the left-hand side of the equation and multiplying both sides by $\mathbf{i}$, we obtain $\mathbf{Dq}=\mathbf{x}$.

From the use matrix, total commodity output (q_i) is the sum of the commodity purchased by all industries (u_{ij}) and the commodity final demand (e_i) or $\mathbf{q}=\mathbf{Ui}+\mathbf{e}$. Since $\mathbf{U}=\mathbf{Tx}$ (see above), total commodity output can be written as $\mathbf{q}=\mathbf{Tx}+\mathbf{e}$. Multiplying both sides of this equation by $\mathbf{D}$ results in $\mathbf{Dq}=\mathbf{DTx}+\mathbf{De}$. We can substitute $\mathbf{Dq}$ by $\mathbf{x}$ and rewrite this equation to obtain $\mathbf{x}=(\mathbf{I}-\mathbf{DT})^{-1}\mathbf{De}$. In the commodity-by-industry IO system, $\mathbf{De}$ can be considered as an equivalent expression for industry final demand ($\mathbf{f}$) in the ordinary IO system (Miller and Blair, 2009). This assumption leads to $\mathbf{x}=(\mathbf{I}-\mathbf{DT})^{-1}\mathbf{f}$, where $\mathbf{DT}$ is an industry-by-industry matrix representing inputs from industries per dollar worth of industry output. This matrix is equivalent to the technical coefficients matrix ($\mathbf{A}$) in the ordinary IO system. $(\mathbf{I}-\mathbf{DT})^{-1}$ acts as an industry-by-industry total requirement matrix that relates industry final demand ($\mathbf{f}$) to total industry output ($\mathbf{x}$) (Miller and Blair, 2009).

2.2.2. Supply-side Input-Output Modelling

Leontief (1936) formulated the IO model assuming an economy with unlimited resources. By using fixed input coefficients, this model aims to analyze the impacts of changes in final demand on the production of every sector (Leontief, 1936). However, in the case of limited resources such as water, an alternative approach is required that relates the changes in each sector's inputs to the production of the same sector and other sectors. An alternative input-output model was therefore proposed by Ghosh (1958) to address these conditions. This model is known as *the supply-side IO (SIO) model*, as opposed to the Leontief demand driven IO model. This approach assumes fixed output coefficients to relate changes in value added such as sectoral primary input in one sector to the production of that same and other sectors (Miller and Blair, 2009). In the Leontief production function, which is a perfect complements production function (i.e., a special case of the constant elasticity of substitution), inputs are assumed not to be substitutable due to the fixed proportion of inputs. Therefore, a change in the technical rate of substitution imposes a constant change in the proportion of inputs of the production structure (Miller and Blair, 2009). This assumption is relaxed in the supply-side IO model as the input coefficients are not fixed (Davis and Salkin, 1984). Both the Leontief and supply-side IO models evaluate the direct and indirect economic impacts of exogenous changes. Direct impacts affect a part of the sectoral production that is directly used as final demand, while indirect impacts affect a part of the sectoral production that is consumed as intermediate products (i.e., purchased by other sectors to produce their output) (Miller and Blair, 2009).

In the SIO model, the traditional technical coefficients are replaced with *allocation* or direct output coefficients. The matrix of allocation coefficients is represented as $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{Z}$ in which $[b_{ij}]$ denotes the inter-industry flows from i to j where the output of sector i provides inputs to other sectors j. In this matrix, instead of dividing each column of $\mathbf{Z}$ by the sum of that column's outputs, which is the way in which matrix $\mathbf{A}$ is calculated in the Leontief IO model, each row of Z is divided by the sum of outputs of that row. To relate the sectoral output and value added, Eq. (2.2) can be rewritten as $\mathbf{x}^{\mathrm{T}} = \mathbf{i}^{\mathrm{T}}\mathbf{Z} + \tilde{\mathbf{v}}^{\mathrm{T}}$ where $\tilde{\mathbf{v}}^{\mathrm{T}}$is the transposed row vector of the sectoral value added. By substituting $\mathbf{Z} = \mathbf{B}\hat{\mathbf{x}}$ in this equation we obtain $\mathbf{x}^{\mathrm{T}} = \tilde{\mathbf{v}}^{\mathrm{T}}(\mathbf{I} - \mathbf{B})^{-1}$ or:

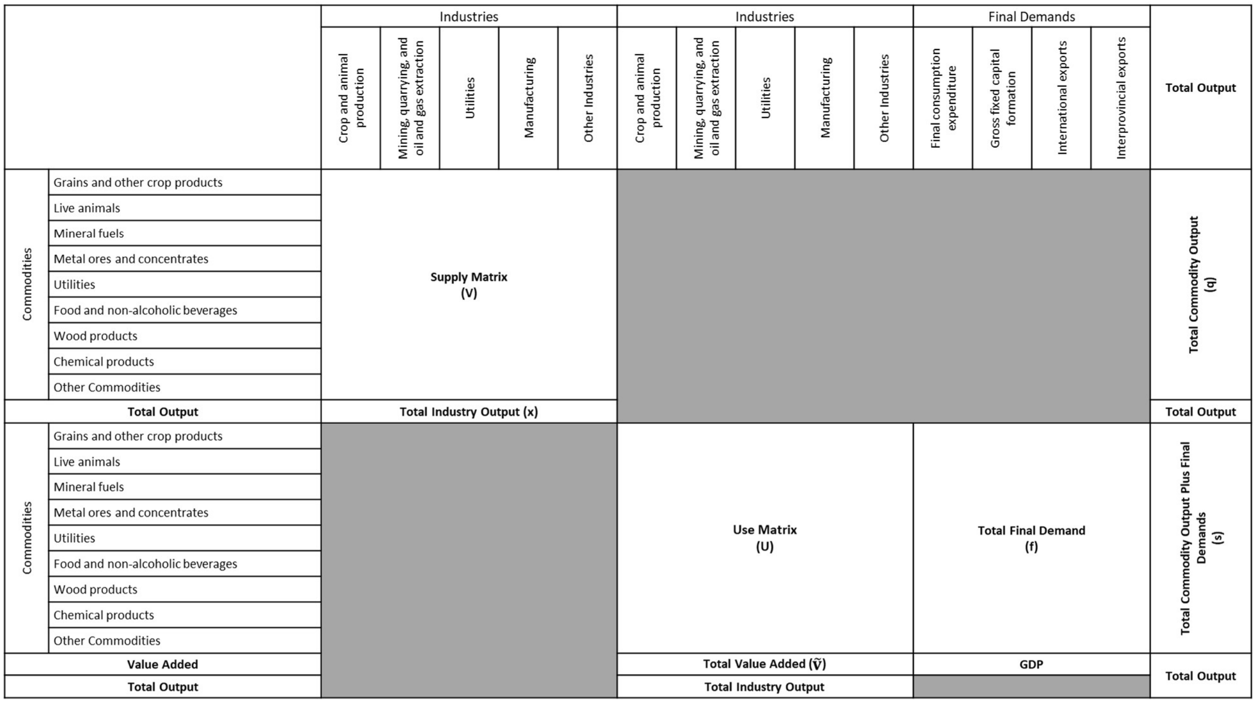
$$\mathbf{x} = (\mathbf{I} - \mathbf{B}^{\mathrm{T}})^{-1}\tilde{\mathbf{v}} \tag{2.4}$$

where $(\mathbf{I} - \mathbf{B}^{\mathrm{T}})^{-1}$ is known as *the output inverse* (Miller and Blair, 2009). Eq. (2.4) enables us to determine variations in gross sectoral production resulting from a unit change in the sectoral primary inputs. To derive the SIO model from the commodity-by-industry tables, we extract total output of industries and commodities from the supply table $\mathbf{V}$ as mentioned in section 2.1.

To generate a square matrix that can be considered as the substitute for the allocation coefficient matrix $\mathbf{B}$ in a rectangular IO system, let $\mathbf{H} = \hat{\boldsymbol{q}}^{-1}\mathbf{U}$, and $\mathbf{C} = \mathbf{V}\hat{\mathbf{x}}^{-1}$. In the case of supply and use tables with m commodities and n industries (i.e., a $m \times n$ supply or use table), both $\mathbf{H}$ and $\mathbf{C}$ are $m \times n$ matrices. $\mathbf{B}^{\mathrm{T}}$ can be replaced by $\mathbf{H}^{\mathrm{T}}\mathbf{C}$, which is an industry-by-industry ($n \times n$) matrix. Thus, the SIO model in a commodity-by-industry format would be as follows:

$$\mathbf{x} = (\mathbf{I} - \mathbf{H}^{\mathrm{T}}\mathbf{C})^{-1}\tilde{\mathbf{v}} \tag{2.5}$$

Figure 2.1 presents the IO structure, the matrices and vectors that have been used in the model development and implementation.



<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="5">Industries</td><td colspan="5">Industries</td><td colspan="4">Final Demands</td><td rowspan="2">Total Output</td></tr>
<tr><td>Crop and animal production</td><td>Mining, quarrying, and oil and gas extraction</td><td>Utilities</td><td>Manufacturing</td><td>Other Industries</td><td>Crop and animal production</td><td>Mining, quarrying, and oil and gas extraction</td><td>Utilities</td><td>Manufacturing</td><td>Other Industries</td><td>Final consumption expenditure</td><td>Gross fixed capital formation</td><td>International exports</td><td>Interprovincial exports</td></tr>
<tr><td rowspan="9">Commodities</td><td>Grains and other crop products</td><td colspan="5" rowspan="9">Supply Matrix
(V)</td><td colspan="9" rowspan="10"></td><td rowspan="9">Total Commodity Output
(q)</td></tr>
<tr><td>Live animals</td></tr>
<tr><td>Mineral fuels</td></tr>
<tr><td>Metal ores and concentrates</td></tr>
<tr><td>Utilities</td></tr>
<tr><td>Food and non-alcoholic beverages</td></tr>
<tr><td>Wood products</td></tr>
<tr><td>Chemical products</td></tr>
<tr><td>Other Commodities</td></tr>
<tr><td colspan="2">Total Output</td><td colspan="5">Total Industry Output (x)</td><td>Total Output</td></tr>
<tr><td rowspan="9">Commodities</td><td>Grains and other crop products</td><td colspan="5" rowspan="11"></td><td colspan="5" rowspan="9">Use Matrix
(U)</td><td colspan="4" rowspan="9">Total Final Demand
(f)</td><td rowspan="9">Total Commodity Output Plus Final Demands
(s)</td></tr>
<tr><td>Live animals</td></tr>
<tr><td>Mineral fuels</td></tr>
<tr><td>Metal ores and concentrates</td></tr>
<tr><td>Utilities</td></tr>
<tr><td>Food and non-alcoholic beverages</td></tr>
<tr><td>Wood products</td></tr>
<tr><td>Chemical products</td></tr>
<tr><td>Other Commodities</td></tr>
<tr><td colspan="2">Value Added</td><td colspan="5">Total Value Added ($\tilde{\mathbf{v}}$)</td><td colspan="4">GDP</td><td rowspan="2">Total Output</td></tr>
<tr><td colspan="2">Total Output</td><td colspan="5">Total Industry Output</td><td colspan="4"></td></tr>
</table>

Figure 2.1. The structure of the IO table, including its matrices and vectors

2.2.3. Spatial Scaling of the Input-Output Model

The provincial IO tables are typically available at a high aggregated scale, appropriate and useful to mimic the economic reaction of a province to exogenous changes. These tables, however, need to be spatially disaggregated to properly reflect the economic impacts of changes in water resources within finer biophysical boundaries such as hydrological sub-basins instead of administrative boundaries (Brouwer et al., 2005). We disaggregate the provincial IO tables into hydrological sub-basins by assuming in a first step that the volume and flow of each sector's production within a sub-basin follow the pattern of the labor force distribution in that sub-basin. Let $\delta_i^r = \frac{l_i^r}{l_i}$, where l_i^r represents the number of the labor force in sector i in sub-basin r, l_i is the total labor force in sector i in the province, and δ_i^r is the sub-basin coefficient and denotes the fraction of the labor force in sector i concentrated in sub-basin r. Supply and use tables for sub-basin r can then be calculated as follows: $\mathbf{V}^r = \mathbf{V}\widehat{\boldsymbol{\delta}}^r$ and $\mathbf{U}^r = \mathbf{U}\widehat{\boldsymbol{\delta}}^r$.

In a second step, we use the regional trade flows within the provinces to estimate trade flows between sub-basins and create inter-sub-basin supply and use tables. The trade flow between two regions multiplied by the labor force ratio (for supply tables) and the population ratio (for use tables) is used as a coefficient to extract the inter-sub-basin tables from the regional tables created in the first step. To extract inter-sub-basin supply tables, we assume that the trade flow between two sub-basins follows the commodity supply description of the origin sub-basin, while in use tables we assume that the inter-sub-basin trade flow follows the consumption pattern of the commodity in the destination sub-basin.

Having intra- and inter-regional supply and use tables, we define the disaggregated provincial allocation coefficient matrix into k sub-basins as follows:

$$\mathbf{B} = \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1\mathrm{k}} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{\mathrm{k}1} & \cdots & \mathbf{B}^{\mathrm{kk}} \end{bmatrix} \tag{2.6}$$

where each element $[B^{r_1r_2}]$ represents a $n \times n$ sub-matrix of intra-regional ($r_1=r_2$) or inter-regional ($r_1 \neq r_2$) allocation coefficients. The dimension of matrix $\mathbf{B}$ with n sectors and k sub-basins is $(n \times k) \times (n \times k)$. Eq. (2.4) can then be written as:

$$\begin{bmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^k \end{bmatrix} = \left\{ \begin{bmatrix} \mathbf{I} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{I} \end{bmatrix} - \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{k1} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{1k} & \cdots & \mathbf{B}^{kk} \end{bmatrix} \right\}^{-1} \begin{bmatrix} \tilde{\mathbf{v}}^1 \\ \vdots \\ \tilde{\mathbf{v}}^k \end{bmatrix} \tag{2.7}$$

In the case of a river basin shared by multiple (m) provinces, the allocation matrix would consist of $m \times m$ submatrices, including intra- and inter-provincial coefficient matrices. Elements of intra-provincial matrices (such as $[b_{ij}^{11}]$) denote the amount of purchase from sector i in one province per monetary unit of output of sector j in the same province. To capture flows of goods and services from sectors in one province to the sectoral production of other provinces, inter-provincial coefficient matrices (such as $\mathbf{B}^{12}$ and $\mathbf{B}^{21}$) are also required.

The process of generating inter-provincial coefficient matrices in this study is based on two key assumptions. First, we assume that a fraction of the sectoral production in each province is exported to sectors in other provinces according to the amount of total trade flow between the corresponding provinces. Second, we assume that the sectoral production in each province is consumed in other provinces according to the destination provinces' consumption pattern of these goods and services. In the case of two provinces, let $\boldsymbol{g}^{12} = [g_{ij}^{12}]$ be the sectoral imports from sector i in province 1 used by sector j in province 2. The inter-provincial supply matrix from province 1 to province 2 can be defined as $(\mathrm{V})^{12} = \left(\widehat{\boldsymbol{g}^{12}}\right)(\widehat{\boldsymbol{q}}^{1})^{-1}(\mathbf{V})^{1}$, where $(\mathbf{V})^{1}$ is the supply matrix of province 1, and $\widehat{\boldsymbol{q}}^{1}$is the diagonal matrix of total commodity production in this province ($(\mathbf{V})^{1}$row sums). The supply matrix of province 1 then has to be adjusted by subtracting the fraction exported to province 2, i.e., $(\mathbf{V})^{12}$.

To extract inter-provincial use matrices in the two provinces case, let $\widehat{\boldsymbol{s}}^{1}$ represent the total intermediate commodity consumption plus final demands in province 1 (row sums of the use table including final demands). The provincial final demands are disaggregated to sub-basin scale using the proportion of provincial population in each sub-basin to make them compatible and comparable with the disaggregated supply and use tables. The inter-provincial use matrix for provinces 1 and 2 is then presented as $(\boldsymbol{U})^{12} = \left(\widehat{\boldsymbol{g}^{12}}\right)(\widehat{\boldsymbol{s}}^{1})^{-1}(\boldsymbol{U})^{1}$. The use matrix of province 1 needs to be adjusted by subtracting the proportion consumed in the second province. Based on the integrated provincial supply and use matrices generated above, we define the SIO model according to Eq. (2.5).

2.2.4. Including Water in the Input-Output Model

To assess the economic impacts of water supply restrictions due to climate and policy change, sectoral water intake, as an indicator of the amount of water supplied to each sector, is included in the SIO model. Raw water, which is a primary input for the production of goods and services is not included in the IO tables because it is typically considered a free resource and its price is equal to the cost of accessing and distributing water. However, changes in the amount of raw water intake can impose constraints on the gross output of an economy (González, 2011; Renzetti and Dupont, 2017). To include water in the IO model, water intake data available in physical units (million cubic meters (MCM)) are converted into monetary units (million dollars) by using water productivity as the ratio of gross sectoral output per physical unit of water. Let $p_i = \frac{x_i}{w_i}$, where p_i is the productivity of raw water intake in million dollars/MCM, x_i is the gross output of sector i in million dollars, and w_i is raw water intake by sector i in MCM. Water use productivity is estimated for rain-fed agriculture using the same method except that the amount of raw water intake is changed to the precipitation amount in millimeters (mm). Then assuming that sectors are not allowed to trade water, nor are they capable of buying water from external sources, we estimate the value of a change in the amount of raw water intake in industry and irrigated agriculture or precipitation in the case of rain-fed agriculture, $\Delta\mathbf{w}$, using the productivity ($\mathbf{p}$) as follows: $\Delta\mathbf{v}_{\mathrm{w}} = \mathbf{p}\Delta\mathbf{w}$. This value change can be considered an exogenous change in the primary input (the right hand side of Eq. (2.5)) and hence linked to gross sectoral product. We assume that other primary inputs remain fixed. Thus, the estimated changes in the sectoral gross output due to changes in water intake (supply) are:

$$\Delta\mathbf{x} = (\mathbf{I} - \mathbf{H}^{\mathrm{T}}\mathbf{C})^{-1}\Delta\mathbf{v}_{\mathrm{w}} \tag{2.8}$$

2.3. Inter-regional supply-side input-output model for the Saskatchewan River Basin

Draining an area of 405,864 km^2, the Saskatchewan River Basin (SaskRB) is a large and multi-jurisdictional river basin that spans three Canadian provinces: Alberta, Saskatchewan, and Manitoba, and a small portion in Montana State in the United States. Alberta and Saskatchewan encompass 94% of this river basin, while Manitoba covers the small remaining part. The SaskRB consists of two main sub-basins, namely the North Saskatchewan and South Saskatchewan river basins. In this study, these sub-basins are disaggregated into six hydro-economic regions across the three provinces following the basin's hydrological and administrative boundaries: the North Saskatchewan (AB-NSRB) and South Saskatchewan (AB-SSRB) sub-basins in Alberta; the North Saskatchewan (SK-NSRB), South Saskatchewan (SK-SSRB), and Saskatchewan River (SK-SRB) sub-basins in Saskatchewan; and the Saskatchewan River Sub-basin (MB-SRB) in Manitoba (see Figure 2.2).

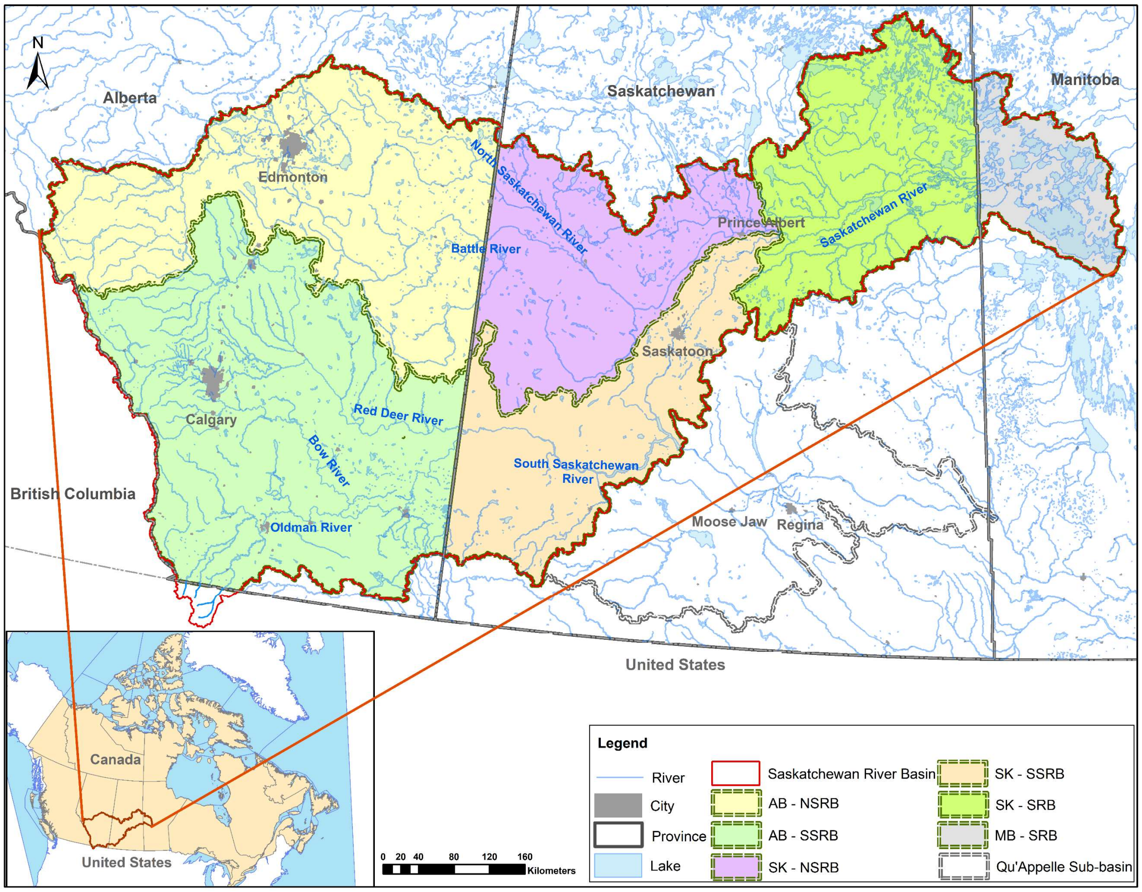


Figure 2.2. The location of the Saskatchewan River Basin in Canada and its six hydro-economic regions across three provinces

Figure 2.3 shows the development process of the inter-regional SIO model for the SaskRB. As can be seen in this figure, the most recent available provincial supply and use tables for the year 2014 from Statistics Canada (2018a) were used to develop the SIO model for the SaskRB (step 1). Statistics Canada generates annual supply and use tables in monetary units (millions of dollars) based on the observed industrial data at both national and provincial scales. These tables are available at different levels of aggregation: summarized and more detailed. The summary level of these tables was used in this study because of the limited water use data that do not allow for a more detailed industry classification. This level of aggregation consists of 35 industries and 66 commodities.

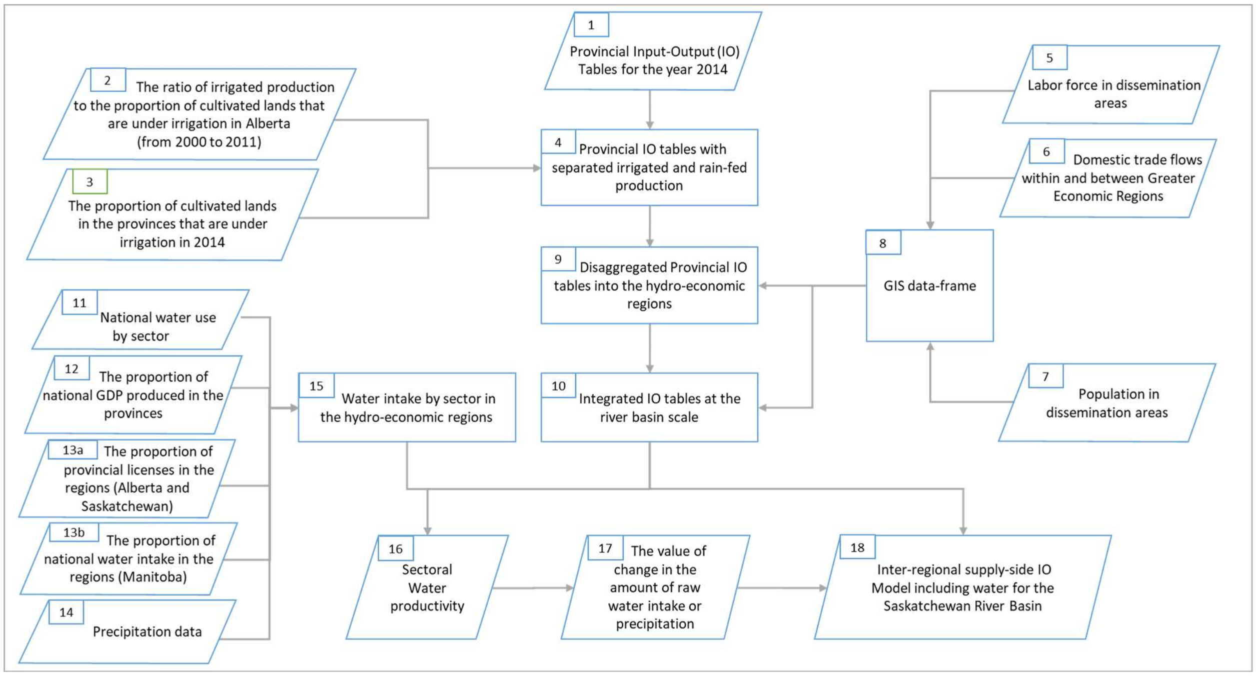


Figure 2.3. Flow diagram depicting the development of the inter-regional supply-side Input-Output model for the Saskatchewan River Basin

The available supply and use tables consider the “crop and animal production” sector without making a distinction between irrigated and rain-fed production. The latter is considered highly relevant for assessing the impacts of possible future water supply restrictions. Irrigated and rain-fed agriculture are expected to respond differently to changes in the amount of available water. Irrigated agriculture is heavily dependent on water intake from surface and groundwater resources, while rain-fed agriculture relies mainly on precipitation. Thus, in the absence of reliable data on crop and animal production with and without irrigation, we disaggregated the total production of the crop and animal sector into irrigated and rain-fed production using the results from a study that was conducted for the Alberta Irrigation Project Association in 2015 (step 2). This study showed that although less than 5% of cultivated lands in Alberta are under irrigation, the production of irrigated lands contributed about 19% to the total production from 2000 to 2011 (Paterson Earth & Water Consulting, 2015). We assume that this proportion remains constant over time and across the three provinces in the absence of other province-specific data. Based on this assumption, the ratio of irrigated land to the total area of cultivated land in the three provinces was estimated using data from Statistics Canada, 2018b, Statistics Canada, 2018c agricultural census (steps 3 and 4 in

Figure 2.3). Since the agricultural census was conducted in 2011 and 2016, the irrigated and total cultivated area were averaged over these two years in the SIO model for 2014. This resulted in 23.0, 1.6, and 2.7% of total agricultural production being under irrigation in Alberta, Saskatchewan, and Manitoba, respectively.

The provincial supply and use tables were then disaggregated into the six hydro-economic regions using coefficients that were calculated based on the labor force data (step 5) from Statistics Canada's 2016 population census across the so-called "census dissemination areas" (Statistics Canada, 2017a). A dissemination area is "the smallest standard geographic area for which all census data are disseminated" (Statistics Canada, 2018d, p.89). In Alberta, 4939 dissemination areas fall completely within the Saskatchewan River Basin (2132 in the AB-NSRB and 2807 in the AB-SSRB). This number of dissemination areas is 971 in Saskatchewan (312 in the SK-NSRB, 568 in the SK-SSRB, and 91 in the SK-SRB) and 29 in Manitoba. In cases where dissemination areas cross the boundaries of the hydro-economic regions (this is the case for 4% of the dissemination areas), the proportion of the dissemination area that falls inside the region was used to estimate the share of the labor force in the dissemination area within that region. Subsequently, the region coefficients were calculated as the fraction of the total sectoral labor force in the province that is concentrated in each region.

In addition to the labor force data, we used the domestic trade flows within and between greater economic regions obtained from Statistics Canada (2018e) to create the inter-regional supply and use tables (step 6). Greater economic regions are aggregated economic regions consisting of census divisions for analyzing economic activities (Statistics Canada, 2018d). Although the matrix structure of the SIO model links regions in each province, these linkages need to be adjusted according to the actual trade flows between the regions. Therefore, labor force and population coefficients (step 7) were used to extract inter-regional trade flows from the available trade flow data between greater economic regions from 2004 to 2012. The average trade flow over this time period was taken to represent the trade flow within and between the greater economic regions in this study for the year 2014. These inter-regional trade flows were then used to link the IO tables of regions within the provincial models (steps 9 and 10). Population data in the census dissemination areas from the 2016 population census was also used to spatially disaggregate provincial final demand. The 2016 census dissemination areas, greater economic regions, hydro-economic regions, and the three provinces in the SaskRB are shown in Figure 2-A-1 in the Annex to this chapter (Section 2-A-1).

The spatial analysis to estimate trade flow, labor force, and population coefficients in the regions was implemented within a Geographic Information System (GIS) data-frame developed specifically for the SaskRB in an ArcGIS platform (step 8 in Figure 2.3). The labor force and population coefficients for the regions in each province are shown in Table 2-A-1, Table 2-A-2 in the Annex to this chapter, respectively. In addition to the hydro-economic regions in each province, the rest of the province (RST) is considered as a separate region to show parts of the provinces that are not located in the SaskRB. The disaggregated provincial supply and use tables, including examples of these spatially disaggregated supply and use tables, and the integrated matrices across the three provinces are also presented in the Annex to this chapter (Sections 2-A-2 and 2-A-3).

The resulting distribution of GDP across the six regions and the estimated GDP for the SaskRB as a whole are presented in Figure 2.4. GDP has a different color and pattern for each province and GDP per province consists of the sum of the preceding GDP values across the regions and includes the rest of the province. Total GDP for the SaskRB as a whole equals the sum of the six hydro-economic regions (and excludes the rest of the provinces that does not fall inside its hydrological boundaries) and was 365 billion Canadian dollars in 2014. Seventy-three percent of GDP in all three provinces taken together was generated in 2014 in the SaskRB. Eighty-eight percent of this total GDP in the SaskRB is generated in the two regions in Alberta, and almost 12% in the three regions in Saskatchewan. The share of GDP generated in Manitoba is less than 0.2%.

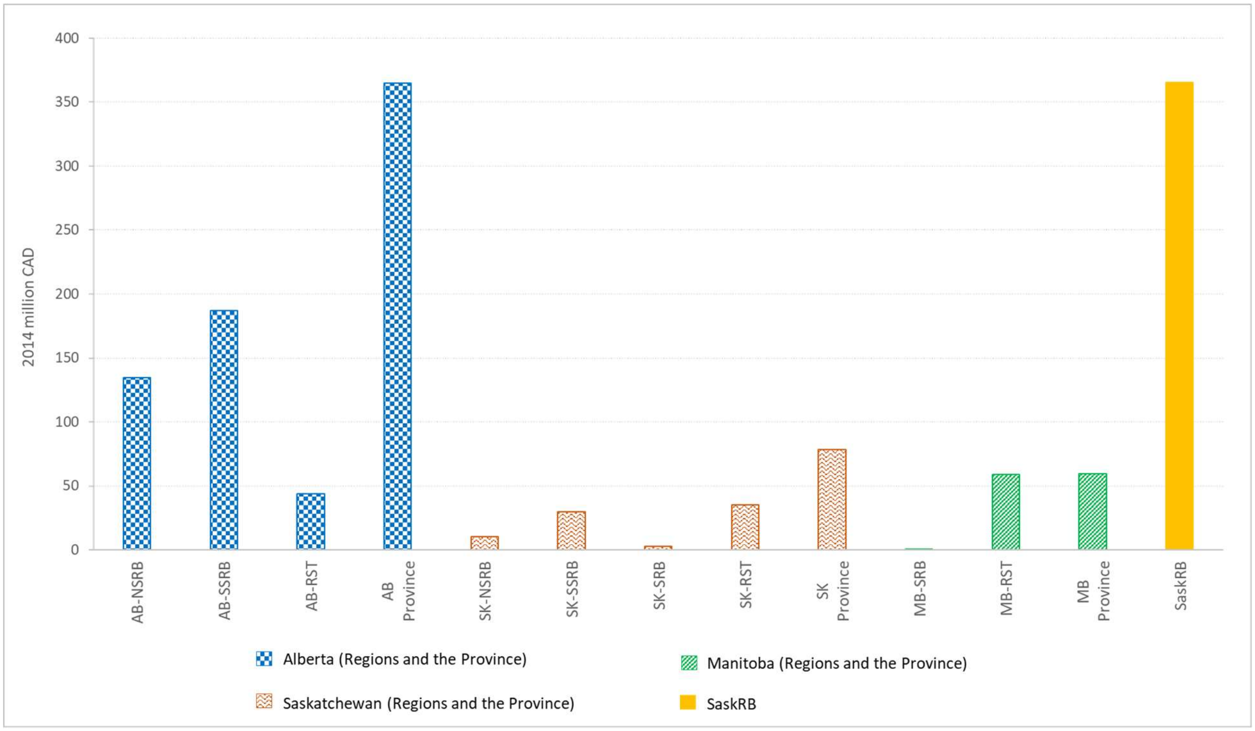


Figure 2.4. Distribution of GDP across the hydro-economic regions in the Saskatchewan River Basin (SaskRB)

After disaggregating the provincial IO tables into the six regions and integrating them again to create the SIO model for the entire SaskRB, we included water intake as an indicator of the amount of water supply to each sector in the SIO model (step 15). Water use data for the SaskRB were obtained from two sources: the provincial water authorities and Statistics Canada. The Saskatchewan Water Security Agency (SWSA) and Alberta Environment and Parks (AEP) collect water use data in the SaskRB since 2002 and 2005, respectively. However, when trying to synthesize the provincial water use data, we faced two main challenges. The first challenge was that each province uses a different system of industry classification for identifying the purpose of water use. For example, the SWSA categorizes almost all manufacturing activities under “Manufacturing” and oil and gas activities under “Oil & Gas”, while AEP categorizes oil and gas activities as “Industrial” uses and does not list any of the other manufacturing sectors. These differences make it challenging to successfully integrate provincial water use data across the whole SaskRB. The second challenge was that some of the users have not reported (or reported inaccurately) their actual amount of water use to the provincial authorities. This causes the provincial water use data to be incomplete and unreliable to represent the total amount of actual water use by the different sectors. The other source of water use data is Statistics Canada that has published national water use data by sector in their "Physical Flow Account for Water Use" every two years from 2009 to 2015. These data are compatible with the same industry classification used in the IO tables, but they are only available biannually and at the national level. They were nevertheless used in this study since no other data for sectoral water use in the SaskRB are available (step 11).

To estimate the provincial raw water intake by sector in 2014 from these national data, the following steps were taken. First, the average of the 2013 and 2015 water use data obtained from Statistics Canada (2018f) was calculated for 2014 at the national level. Next, the proportion of national gross domestic product (GDP) produced by each sector in each province was used to allocate the amount of sectoral water use from national to provincial level (step 12). National and provincial GDP data were obtained from Statistics Canada (2018g). Then, sectoral water intake in the various regions was extracted from the provincial water use data in two different ways. For Alberta and Saskatchewan, the ratio of allocated water licenses in the sub-basins obtained from the SWSA (2018) and AEP (2018) was used (step 13a). Since water license data were not available for Manitoba, we used the proportion of national water intake from surface water resources available from Statistics Canada (2017b) for the region in this province and considered this proportion constant across the sectors (step 13b). Raw water intake in the regions of the SaskRB is considered for five main sectors: irrigated crop and animal production; mining, quarrying, and oil & gas extraction; utilities; construction; and manufacturing. Other sectors mainly receive water from the utilities sector, the monetary economic flows of which are already included in the IO tables. These data and assumptions were used here despite their implications for the results because no other data were available for water intake in the SaskRB at the time of this study. However, after connecting the model to a water resources model (Chapters 4 and 5), these water intake data were extracted from the results of that model, and the assumptions explained above were relaxed.

In addition to the water intake and production of the SaskRB, a part of The Qu'Appelle River Sub-basin was also considered in the SIO model. The Qu'Appelle River Sub-basin (the gray dotted double line sub-basin in Figure 2.2) is not hydrologically a part of the SaskRB. However, water is diverted from the South Saskatchewan River to this sub-basin to meet a portion of its water demand. Thus, we estimated the production of the Qu'Appelle River Sub-basin that was a result of the diverted water, by using the proportion of licenses in this sub-basin allocated from the SK-SSRB. This proportion was then applied to the coefficients of the SK-SSRB to disaggregate the provincial IO tables.

Along with the raw water intake, precipitation during the 2014 crop season was also considered for the rain-fed crop and animal production sector (step 14). The precipitation data for the SaskRB were taken from the Canadian Precipitation Analysis (CaPA) dataset (Mahfouf et al., 2007; Fortin et al., 2015; Fortin et al., 2018). These gridded precipitation data were then extracted for the cultivated areas in each region using the GIS data-frame to estimate the amount of precipitation in the regions. The raw water intake and precipitation data for the main sectors in the six hydro-economic regions are presented in Table 2.1.

Table 2.1. Raw water intake by sector and precipitation in rain-fed agricultural production in the six hydro-economic regions of the Saskatchewan River Basin in 2014.

Province-Region	Industry					
	Irrigated - Crop and animal production (MCM)	Rain-fed - Crop and animal production (mm)	Mining, quarrying, and oil and gas extraction (MCM)	Utilities (MCM)	Construction (MCM)	Manufacturing (MCM)
AB-NSRB	3	321	58	447	0.3	393
AB-SSRB	379	337	33	2055	1	38
AB-RST	6	360	492	257	0.2	70
Total AB	388	1018	582	2759	2	501
SK-NSRB	25	369	3	19	0.01	57
SK-SSRB	280	364	54	930	0.3	22
SK-SRB	2	411	0.2	2	0.001	1
SK-RST	171	402	58	68	0.02	15
Total SK	478	1546	116	1019	0.4	96
MB-SRB	0.1	421	0.01	1	0.0001	0.1
MB-RST	20895	469	1368	121647	27	12712
Total MB	20895	890	1368	121648	27	12713

Note: Five construction sectors were integrated into “Construction”. Irrigated crop and animal production also includes forestry and logging, fishing, hunting and trapping, and support activities for agriculture and forestry.

Raw water intake and precipitation data generated in the previous steps were then used along with sectoral production to calculate water productivity and the value of change in the amount of raw water intake and precipitation, as explained in Section 2.2.4 (steps 16 and 17). This value of change was applied to estimate the changes in sectoral gross output due to changes in water intake through Eq. (2.8) (step 18).

The main characteristics of the six regions in the SaskRB are summarized in Table 2.2. As can be seen, the AB-SSRB and SK-SSRB have the highest shares of the labor force (52% and 40%, respectively), population (51% and 31%, respectively), and raw water intake (59% and 75%, respectively). In Saskatchewan, slightly more than half of the population (51%) and 44% of the labor force are distributed in the rest of the province (SK-RST). Since only a small share of the SaskRB is located in Manitoba, the labor force, population, and raw water intake in this part of the Saskatchewan River Basin are small, i.e., 1, 1, and 0.001%, respectively.

Table 2.2. Distribution of key socio-economic and hydrological variables across the six regions in the Saskatchewan River Basin and the rest of the provinces.

Province-Region	Hydro-Economic Region Characteristics (%)						
	Labor Force	Population	Export	Import	Raw Water Intake	Precipitation	Production
AB-NSRB	38	39	46	36	21	32	37
AB-SSRT	52	51	41	44	59	33	51
AB-RST	10	10	13	19	19	35	12
AB	100	100	100	100	100	100	100
SK-NSRB	13	14	13	15	6	24	13
SK-SSRB	40	31	37	37	75	24	38
SK-SRB	3	4	3	4	0.3	27	4
SK-RST	44	51	47	44	18	26	46
SK	100	100	100	100	100	100	100
MB-SRB	1	1	5	5	0.001	47	1
MB-RST	99	99	95	95	99.999	53	99
MB	100	100	100.0	100.0	100.0	100.0	100.0

2.4. Modelling Assumptions and Limitations

As mentioned briefly in Section 2.2.2, this study deals with managing limited water resources, while the Leontief Input-Output (IO) model is formulated based on the assumption of an economy with unlimited resources. Therefore, the supply-side IO alternative was applied here, which estimates the impacts of changes in primary inputs on sectoral production using fixed output coefficients (Ghosh, 1958). The Leontief production function is a perfect complements production function, where inputs are assumed not to be substitutable due to the fixed proportion of inputs. Therefore, a change in the technical rate of substitution imposes a constant change in the proportion of inputs of the production structure (Miller and Blair, 2009). This seriously undermines the use of, for example, water-saving technologies in the models to improve the water productivity, or the productivity of any other input factor, or the substitution of production factors (e.g., capital with labor).

In the supply-side IO model, the model is designed to estimate the impacts of changes in the supply of inputs, while the distribution of outputs in the economy is assumed to be fixed, meaning that a change in a sector's output (as a result of altering its input) imposes a proportionate change in the sales from that sector to the rest of the economy (Davis and Salkin, 1984; Miller and Blair, 2009). In reality, supply and demand are expected to change over time as a result of scarcity and, consequently, the prices of input and output factors. IO models are unable to cope with or account for these market mechanisms to predict new equilibria under changing conditions. The results presented here, therefore reflect expected short-term impacts with no technological adaptations to the new conditions, and hence merely give a snapshot of how the economic output and valued added would change if the imposed water availability restrictions would occur overnight.

In this chapter, the ISIO model is not coupled yet with the water resources system model (MODSIM) (See Chapters 4 and 5), and hence the water intake data were extracted from data published by Statistics Canada (2018). This water intake dataset is bi-annual and only available at the national level. Assumptions, therefore, had to be made in extracting regional water intake data from this national dataset in the absence of other data as described in Section 2.3. These assumptions, such as extracting sectoral water intake proportionate to the sectoral GDP in provinces, extracting water intake in sub-basins according to the ratio of national water intake in sub-basins in each province, interpolating the water intake data of the years 2013 and 2015 to estimate water intake for 2014, etc. will be relaxed when the ISIO model is coupled with the MODSIM model for the SaskRB in the next steps of this dissertation (Chapters 4 and 5).

2.5. Water supply restriction scenarios due to climate and policy change

Since the SIO model for the SaskRB is developed for the year 2014 (the base year of this chapter), the climatic and economic conditions of that year are considered as the baseline scenario in this chapter. The year 2014 was a wet year, and the annual streamflow of, for example, the South Saskatchewan River was 50% higher than its long-term (1912–2015) average. Given the climatic conditions in the base year, we articulated water supply restriction scenarios by assuming that the raw water availability would be reduced by 5.0% (North Saskatchewan Water Alliance, 2008) and 8.5% (Pomeroy et al., 2009) due to climate change in the North and South Saskatchewan Rivers, respectively. This is a relatively moderate reduction compared to the long-term average flow in the SaskRB. We also consider an 8 (North Saskatchewan Water Alliance, 2008) and 11% (Töyrä et al., 2005) drop in precipitation during the crop-growing season caused by climate change in the North and South Saskatchewan sub-basins, respectively. Based on these existing studies investigating the hydrological impacts of future climate change in the North and South Saskatchewan River Basins, the six hydro-economic regions experience the same reduction in water availability depending on whether they are located in either the North or the South Saskatchewan River Sub-basins (e.g., the reduction in water availability in SK-NSRB and AB-NSRB is equal to the water reduction in the North Saskatchewan River Sub-basin).

About 90% of streamflow in the Saskatchewan River comes from its headwaters in the Rocky Mountains (Halliday and Associates, 2009), known as “water towers”, which are geographically different from the prairies and farming centers where summer precipitation includes local, convective storms. Most of the prairie region is non-contributing to the main rivers. In a normal year (neither wet nor dry), 44% of the Saskatchewan River drainage area does not contribute any runoff to the streamflow (Halliday and Associates, 2009).

Based on these conditions, we articulated the first scenario in which climate-change-induced water supply restriction is imposed on all sectors uniformly to evaluate its economic impacts at regional, river basin, and provincial scales. We then assume a number of policy changes in the second scenario that leads to a non-uniform reduction in sectoral water supply to mitigate the economic impacts of this water supply restriction.

Under the first scenario, we assume that raw water supply to all sectors reduces by 5.0 and 8.5% in the North and South Saskatchewan sub-basins, respectively. In this scenario, we do not consider any change in the water allocation policy compared to the baseline scenario. This assumption implies that all sectors are given equal priority in water allocation, and they do not have access to alternative water sources. Additionally, the 8 and 11% reduction in precipitation directly affects the rain-fed crop and animal production sector in the North and South Saskatchewan sub-basins.

Under the second scenario, we consider policy changes along with water supply restrictions caused by climate change. In this scenario, we assume that sectors are given different priorities, and some have access to alternative (substitute) sources for surface water. Based on this assumption, different sectors experience different reductions in their water supply due to the 5.0 and 8.5% reductions in available water, while the rain-fed crop and animal production sector remains directly affected by the 8 and 11% reductions in precipitation in the North and South Saskatchewan sub-basins, respectively. Under this scenario, the utilities sector that provides drinking water takes priority over other sectors, and water supply to this sector is not affected by the lower amount of available water. Since irrigated crop and animal production relies heavily on water supply from surface water resources, the 5.0 and 8.5% reductions in the amount of available water due to climate change reduce raw water supply to this sector proportionately by the same percentage. However, this reduction does not affect water supply to the other sectors in the same way and to the same extent. Manufacturing and mining, quarrying, oil and gas extraction may either have access to alternative water sources, such as groundwater or poorer quality water resources, or may be able to implement water-saving technologies (e.g., water recycling). The actual implementation of these alternative water sources or water saving technologies depends on their incremental costs and benefits but may be e economically more efficient in their water and energy use, and the implementation costs are therefore assumed to be offset by cost-savings here. In this study, raw water supply to these sectors is, therefore, assumed to be reduced only by half of these percentages.

2.6. Economic impacts of the water supply restriction scenarios

Table 2.3 presents the percentage changes in sectoral production in the six hydro-economic regions of the SaskRB and the rest of the provinces under the uniform and non-uniform water supply reduction scenarios. According to this table, the minimum reduction in sectoral output under the uniform scenario is 5% in the utilities sector in MB-SRB, while the impact is felt hardest in rain-fed crop and animal production in AB-SSRB where output falls by almost 21%. As expected, the effects of a water supply reduction are less pronounced under the non-uniform water supply scenario, although production still drops across the SaskRB from 0.1% in the utilities sector in MB-SRB to 18% in rain-fed crop and animal production in AB-SSRB.

Notable is that sectoral production in the rest of the provinces falling outside the SaskRB, where the water supply reduction takes place, is affected too, ranging from 0.2% in the utilities sector in MB-RST to 5% in rain-fed crop and animal production in AB-RST under the first scenario. The same figures are 0.1 to 4% under the second scenario (Table 2.3). The reduction in production in the rest of the provinces under both scenarios without any changes in water supply or precipitation is due to the inter-regional economic connections between the SaskRB's regions and the rest of the provinces.

Another interesting finding is that even though the percentage reduction of raw water supply and precipitation in the irrigated and rain-fed crop and animal sectors is the same in both scenarios, their output is less impacted under the second scenario. Differences in production are lowest in irrigated crop and animal production in SK-RST (0.3%) and highest in rain-fed crop and animal production in AB-SSRB (2.8%). This illustrates the (economic importance of the) level of interconnectedness between the various sectors and inter-regional trade flows, which dampen the impact on the more weather and water dependent sectors. In other words, the output of other water-use sectors, such as manufacturing, less decreased under the second scenario, and hence inputs coming from these sectors to agriculture (both irrigated and rain-fed) improves under this scenario which, consequently, increases the output of agriculture. A related finding of such indirect impacts is the decline in the production of the utilities sector under the second scenario even though water supply to this sector also remains unchanged. The reduction in production in this sector ranges from 0.1% in MB-SRB and MB-RST to 1.6% in AB-SSRB and SK-SSRB (Table 2.3).

Table 2.3. Percentage changes in sectoral monetary production in the six hydro-economic regions of the Saskatchewan River Basin and the rest of the provinces under uniform and non-uniform water supply reduction scenarios.

		Hydro-Economic Region								
Scenario	**Sector**	AB-NSRB	AB-SSRB	AB-RST	SK-NSRB	SK-SSRB	SK-SRB	SK-RST	MB-SRB	MB-RST
Uniform Reduction in Sectoral Water Supply	Irrigated - Crop and animal production	-10.9%	-16.1%	-4.3%	-7.0%	-10.4%	-6.4%	-0.8%	-6.1%	-2.3%
	Rain-fed - Crop and animal production	-15.4%	-20.8%	-5.0%	-13.0%	-17.5%	-12.3%	-1.1%	-11.8%	-2.5%
	Mining, quarrying, and oil and gas extraction	-6.8%	-11.0%	-1.1%	-6.8%	-11.1%	-6.3%	-0.4%	-6.1%	-0.8%
	Utilities	-7.1%	-11.5%	-1.3%	-7.1%	-11.6%	-6.6%	-0.4%	-5.2%	-0.2%
	Construction	-8.7%	-13.7%	-2.4%	-8.4%	-13.1%	-7.5%	-0.8%	-7.6%	-1.7%
	Manufacturing	-10.5%	-16.2%	-3.4%	-10.3%	-15.8%	-9.5%	-1.1%	-8.4%	-1.9%
Non-uniform Reduction in Sectoral Water Supply	Irrigated - Crop and animal production	-9.1%	-13.7%	-3.0%	-5.6%	-8.6%	-5.4%	-0.5%	-5.0%	-1.3%
	Rain-fed - Crop and animal production	-13.3%	-18.0%	-3.6%	-11.3%	-15.2%	-11.0%	-0.7%	-10.4%	-1.5%
	Mining, quarrying, and oil and gas extraction	-3.4%	-5.5%	-0.6%	-3.4%	-5.6%	-3.2%	-0.2%	-3.0%	-0.5%
	Utilities	-1.1%	-1.6%	-0.7%	-1.1%	-1.6%	-0.8%	-0.2%	-0.1%	-0.1%
	Construction	-4.5%	-7.0%	-1.3%	-4.4%	-6.7%	-3.9%	-0.4%	-4.0%	-1.0%
	Manufacturing	-5.8%	-8.7%	-2.1%	-5.9%	-8.8%	-5.5%	-0.7%	-4.7%	-1.3%

Figure 2.5 illustrates the percentage changes in sectoral production at the provincial and entire river basin scales. Under the first scenario, rain-fed crop and animal production faces the highest decline in sectoral production in Alberta, Saskatchewan, Manitoba, and the entire SaskRB (17.1, 8.0, 2.6, and 17.2%, respectively). Under this scenario, irrigated crop and animal production has the second highest drop in sectoral production in Alberta (12.9%) and Manitoba (2.3%), while the second highest reduction in production in Saskatchewan occurs in manufacturing (7.6%). In the SaskRB, irrigated crop and animal production and manufacturing have the second highest decline

in production (13.6%) under the first scenario (Figure 2.5). Under the second scenario, rain-fed and irrigated crop and animal production incur the highest and the second highest declines in production in Alberta (14.7% and 10.8%, respectively), Manitoba (1.6% and 1.4%, respectively), and the whole basin (15.0% and 11.4%, respectively). Saskatchewan also experiences the largest reduction in rain-fed crop and animal production (6.9%) followed by manufacturing (4.3%).

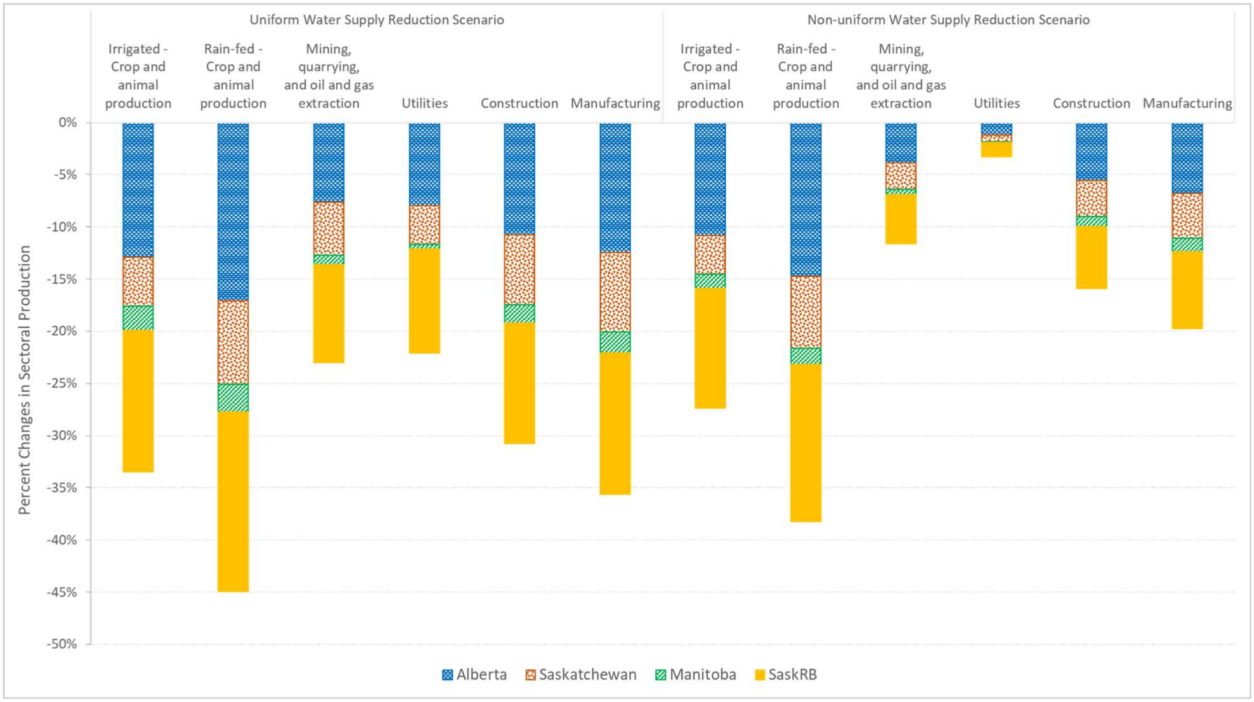


Figure 2.5. Percentage changes in sectoral production in the three provinces and the entire Saskatchewan River Basin under uniform and non-uniform water supply reduction scenarios.

Finally, the percentage changes in GDP in the six hydro-economic regions of the SaskRB under the two scenarios are presented in Figure 2.6. Under the first scenario, the impact on GDP ranges from 4% in MB-SRB to 8% in AB-SSRB, while a lower reduction in GDP across the six regions occurs, as expected, under the second scenario, ranging from 2% in MB-SRB to 5% in SK-SRB. In Alberta, AB-NSRB experiences a lower decrease in GDP under both scenarios (5.0% under the uniform and 2.6% under the non-uniform scenario) than AB-SSRB. In Saskatchewan, SK-SSRB faces the largest drop in GDP under the first scenario (8.0%) followed by SK-SRB (7.9%) and SK-

NSRB (6.0%), while SK-SRB has the largest reduction in GDP (5.2%) under the second scenario, followed by SK-SSRB (4.5%) and SK-NSRB (3.7%).

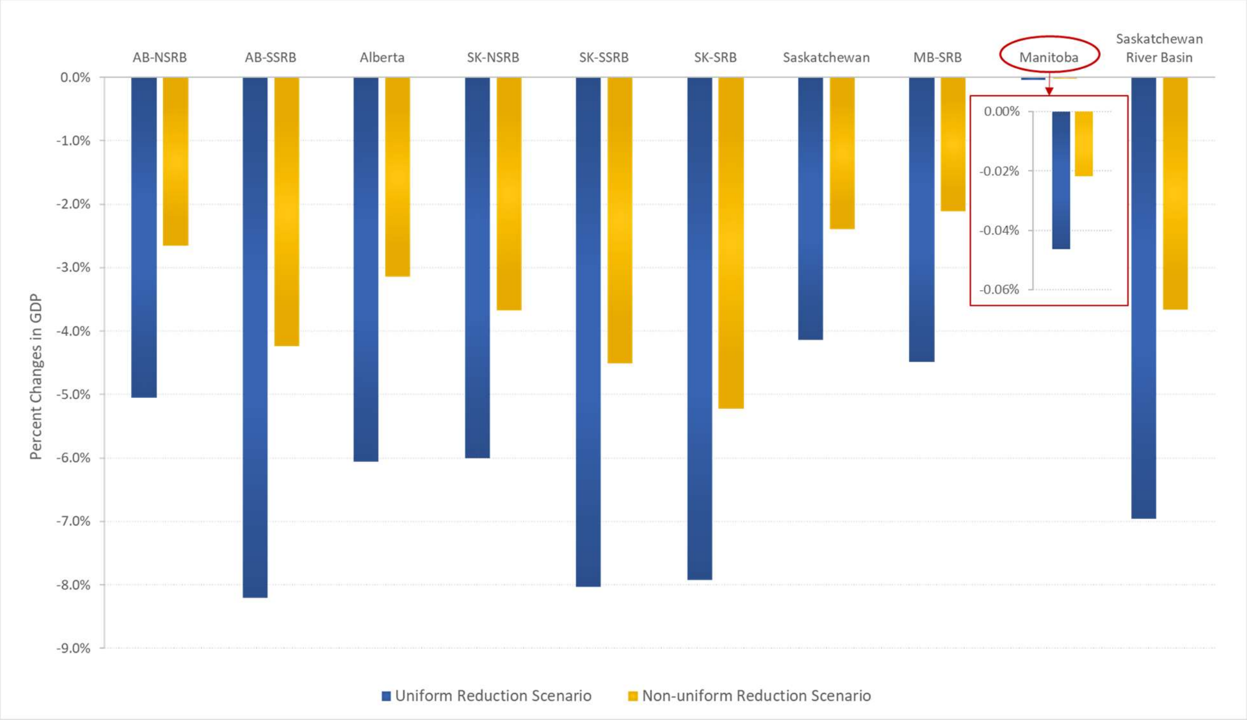


Figure 2.6. Percent changes in GDP in the six hydro-economic regions, provinces, and the entire Saskatchewan River Basin under uniform and non-uniform water supply reduction scenarios.

Aggregated at the level of the three provinces, Figure 2.6 shows that GDP is reduced in Alberta, Saskatchewan, and Manitoba by 6.1, 4.1, and 0.05%, respectively under the first scenario where water supply is reduced uniformly across all sectors in SaskRB (i.e., 5.0% in North Saskatchewan and 8.5% in South Saskatchewan sub-basins). In monetary terms, this means a loss of 22.1 billion Canadian dollars in Alberta, 3.2 billion in Saskatchewan, and 28 million Canadian dollars in Manitoba.

This impact is moderated under the second (non-uniform) scenario, as its associated GDP decreases by 3.1, 2.4, and 0.02%, respectively (11.5 billion, 1.8 billion, and 13 million CAD, respectively). These results hence indicate that by changing water allocation policies in the face of water shortage due to climate change, the potential impact on provincial GDP can be mitigated by between 40 and 60%. Moving from a uniform water supply reduction scenario to a non-uniform scenario also reduces the expected economic losses in the entire SaskRB by almost 50%, i.e., GDP drops 7.0% under the first scenario, while this is only 3.7% under the second scenario. This is equivalent to a reduction in GDP loss of 12 billion Canadian dollar.

2.7. Discussion and conclusions

The hydro-economic model presented in this chapter is the first inter-regional supply-side Input-Output (SIO) model developed for the Saskatchewan River Basin (SaskRB) to evaluate the direct and indirect economic impacts of possible future changes in water supply (both raw water intake and precipitation) across the entire river basin. This transboundary river basin was modelled as an integrated hydro-economic system. Most of the studies that have addressed water supply issues focused on either one type of water demand, such as agriculture, or targeted only one region, mostly a country or a single sub-basin (e.g., Yoo and Yang, 1999; Cai et al., 2003; Kulshreshtha and Grant, 2003; Medellín-Azuara et al., 2007; Boithias et al., 2014; Ward, 2014; Kim and Kaluarachchi, 2016; Sherafatpour et al., 2019). On the contrary, this model considers all water use sectors and inter-regional trade flows to evaluate the economic impacts of changes in water supply on different sectors in both hydrological (i.e., sub-basins and river basins) and administrative units (i.e., provinces).

Using a GIS data-frame, the model allows users to identify economically efficient water policy strategies to mitigate climate change impacts on the entire river basin as well as the three provinces sharing the river. In doing so, the SIO model moves away from the traditional focus on administrative geographical units, such as provinces, to hydrological units such as sub-basins making up the river basin. Previous studies in this field mainly adhered to the administrative boundaries for which economic data are typically available (e.g., Yoo and Yang, 1999; Velázquez, 2006; González, 2011; Bogra et al., 2016), while this study considered and combined both the administrative and hydrological boundaries. This study is also among very few studies that have developed a supply-side IO model to examine the impacts of an exogenous change in water supply as a primary input on the economy (e.g., Yoo and Yang, 1999; González, 2011; Bogra et al., 2016). Furthermore, attempts in the past to develop conventional IO models for this specific river basin only considered a part of the basin such as one sub-basin (e.g., Martz et al., 2007) or a province (e.g., Paterson Earth & Water Consulting, 2015) and focused on examining the impacts of changes in final demand on water consumption (e.g., Martz et al., 2007; Paterson Earth & Water Consulting, 2015; Brown, 2017). The process of aligning the available economic and hydrological data and information along these different spatial boundaries turned out to be particularly challenging given their different temporal and spatial resolutions. To overcome these spatial up- and down-scaling challenges, we used supplementary datasets, namely (1) labor force and population data to disaggregate the provincial supply and use tables to the regional level, and (2) inter- and intra-provincial trade flows to create inter-regional IO tables. Raw water intake by economic sectors was used as an additional factor of production in the model.

The value added of the model was tested by applying the model to study the economic impacts of climate-change-induced water supply restrictions without and with possible changes in water allocation policy. Considering these policy options, we articulated uniform and non-uniform water supply reduction scenarios. The first scenario considered the same (uniform) reduction in water supply in all sectors in the SaskRB without any changes in existing water allocation policy, while the second scenario considered a differential (non-uniform) water supply reduction due to the implementation of alternative policy options. Analyzing the results of these two water supply restriction scenarios, we showed that the estimated economic losses under climate-change-induced water restrictions can be reduced by almost 50% or 12 billion Canadian dollars in the SaskRB by prioritizing sectoral demand and employing supply-side management tools, making use of alternative water sources and best available technologies to recycle and reuse water. To put this mitigation effect in perspective, this loss reduction is 2.4% of GDP generated in Alberta, Saskatchewan and Manitoba taken together. For example, the utilities sector that provides drinking water usually receives first priority in periods of severe droughts (e.g., GWP CEE, 2015). As a result, the production of sectors that receive all or part of their water from this sector would also be less affected by any future water supply restriction than those directly taking their water from surface water resources, such as irrigated agriculture. Another way to reduce the economic impacts of a water supply restriction is to consider alternative water resources. No data are available at local, regional or provincial level, but Statistics Canada (2011) reported that in 2011 the Canadian manufacturing industry took 6% of its water from freshwater sources other than surface water, including groundwater, and slightly less than 5% from saline water. These modest shares suggest that there may be more untapped potential. Additionally, several manufacturing industries in

Canada recirculate water, including primary metals and paper industries. For instance, the amount of recirculated water in the manufacturing sector in Alberta, Saskatchewan, and Manitoba in 2015 was about 189 MCM (Statistics Canada, 2018h). Here too there seems to be promise for expansion to meet future water demand.

Besides exploring sustainable pathways to efficiently allocate limited available water resources among increasingly competing water uses or mitigate the economic impacts of climate change in a multi-jurisdictional context, the integrated hydro-economic model also illustrates the relevance of the interconnections between the six hydro-economic regions making up the SaskRB and the rest of the provinces. Our modelling results showed that water supply restrictions within the basin would affect production not only among sectors within the basin, but also in the rest of the three provinces in which the basin is located. Hence, besides relevant hydrological connections, the spatial economic connectivity between the six regions of the SaskRB and the rest of the provinces cause water supply restrictions in the river basin to also affect economic activities outside of the basin. Understanding these connections and providing insight into how sectoral output in administrative units (e.g., provinces) inside and outside the river basin will be affected by climate-change-induced future water shortages is expected to be of prime interest to water policy and decision-makers to identify cost-effective future policy options and interventions.

Author Contributions

LE and RB conceptualized the method. LE developed the model, wrote the computer codes, designed the numerical experiments, and performed them all. LE and RB contributed to the interpretation of the results. LE wrote the paper. RB and SR contributed to the editing of the paper.

Appendix 2-A

2-A-1

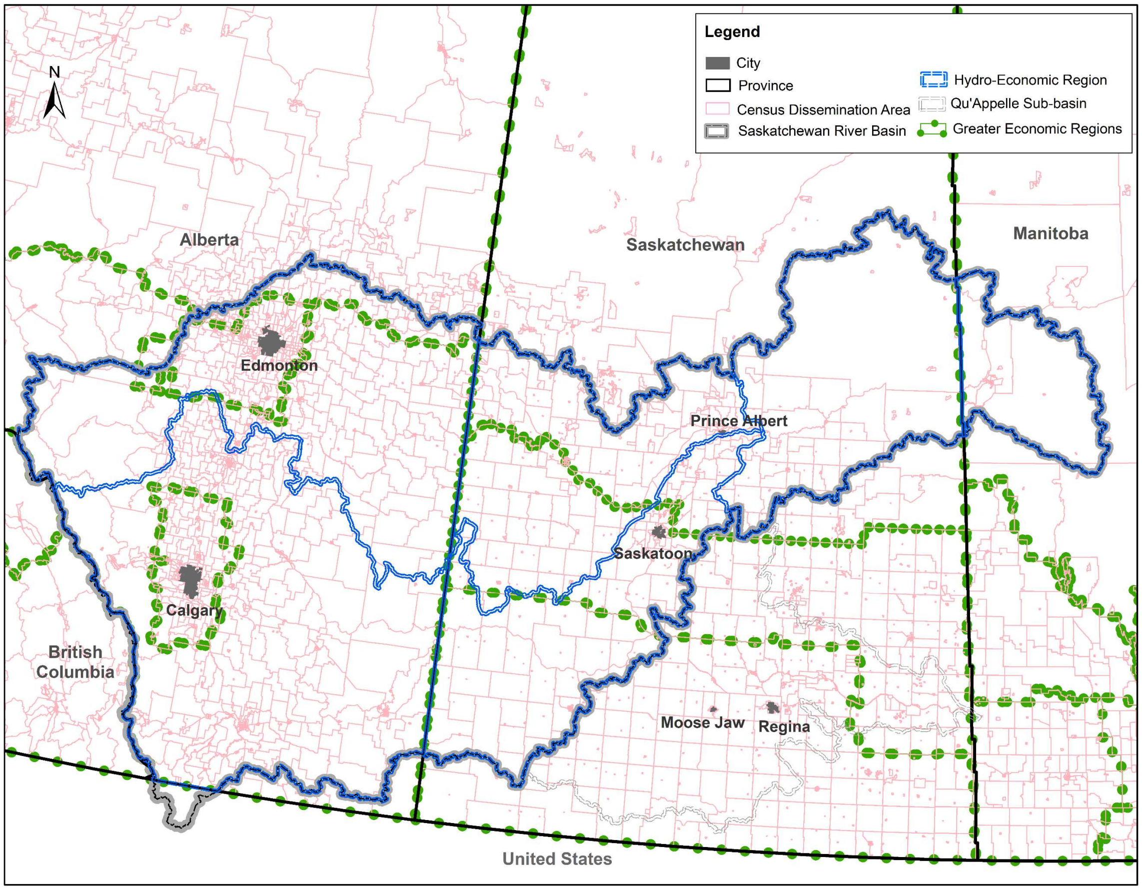


Figure 2-A-1. Census dissemination areas and greater economic regions in the six hydro-economic regions in the three provinces in the Saskatchewan River Basin.

Table 2-A-1. Labor force coefficients used to disaggregate and downscale the provincial Input-Output tables into the hydro-economic regions in the Saskatchewan River Basin.

Province	Alberta (AB)				Saskatchewan (SK)					Manitoba (MB)		
Hydro-Economic Regions / Industry	NSRB	SSRB	RST	AB	NSRB	SSRB	SRB	RST	SK	SRB	RST	MB
Crop and animal production - Irrigated	0.39	0.51	0.10	1.00	0.16	0.26	0.07	0.51	1.00	0.01	0.99	1.00
Crop and animal production – Rain-fed	0.39	0.51	0.10	1.00	0.16	0.26	0.07	0.51	1.00	0.01	0.99	1.00
Forestry and logging	0.39	0.51	0.10	1.00	0.16	0.26	0.07	0.51	1.00	0.01	0.99	1.00
Fishing, hunting and trapping	0.39	0.51	0.10	1.00	0.16	0.26	0.07	0.51	1.00	0.01	0.99	1.00
Support activities for agriculture and forestry	0.39	0.51	0.10	1.00	0.16	0.26	0.07	0.51	1.00	0.01	0.99	1.00
Mining, quarrying, and oil and gas extraction	0.31	0.48	0.22	1.00	0.19	0.31	0.04	0.47	1.00	0.01	0.99	1.00
Utilities	0.25	0.51	0.24	1.00	0.09	0.23	0.02	0.66	1.00	0.06	0.94	1.00
Residential building construction	0.40	0.52	0.08	1.00	0.12	0.39	0.03	0.47	1.00	0.01	0.99	1.00
Non-residential building construction	0.40	0.52	0.08	1.00	0.12	0.39	0.03	0.47	1.00	0.01	0.99	1.00
Engineering construction	0.40	0.52	0.08	1.00	0.12	0.39	0.03	0.47	1.00	0.01	0.99	1.00
Repair construction	0.40	0.52	0.08	1.00	0.12	0.39	0.03	0.47	1.00	0.01	0.99	1.00
Other activities of the construction industry	0.40	0.52	0.08	1.00	0.12	0.39	0.03	0.47	1.00	0.01	0.99	1.00
Manufacturing	0.43	0.47	0.10	1.00	0.07	0.37	0.05	0.51	1.00	0.01	0.99	1.00
Wholesale trade	0.41	0.51	0.08	1.00	0.11	0.39	0.03	0.47	1.00	0.01	0.99	1.00
Retail trade	0.43	0.49	0.08	1.00	0.14	0.35	0.04	0.48	1.00	0.00	1.00	1.00
Transportation and warehousing	0.40	0.51	0.09	1.00	0.14	0.35	0.03	0.48	1.00	0.01	0.99	1.00
Information and cultural industries	0.36	0.53	0.11	1.00	0.07	0.34	0.02	0.57	1.00	0.01	0.99	1.00
Finance, insurance, real estate, rental and leasing and holding companies	0.36	0.59	0.05	1.00	0.10	0.30	0.02	0.58	1.00	0.01	0.99	1.00
Owner occupied dwellings	0.40	0.55	0.06	1.00	0.09	0.43	0.02	0.46	1.00	0.00	1.00	1.00
Professional, scientific and technical services	0.39	0.53	0.09	1.00	0.09	0.46	0.02	0.44	1.00	0.01	0.99	1.00
Administrative and support, waste management and remediation services	0.20	0.76	0.04	1.00	0.11	0.37	0.03	0.50	1.00	0.00	1.00	1.00
Educational services	0.37	0.53	0.09	1.00	0.13	0.41	0.03	0.43	1.00	0.01	0.99	1.00
Health care and social assistance	0.41	0.50	0.09	1.00	0.13	0.35	0.04	0.47	1.00	0.02	0.98	1.00
Arts, entertainment and recreation	0.41	0.51	0.07	1.00	0.14	0.35	0.02	0.49	1.00	0.01	0.99	1.00
Accommodation and food services	0.36	0.57	0.07	1.00	0.12	0.39	0.03	0.46	1.00	0.02	0.98	1.00
Other services (except public administration)	0.38	0.53	0.09	1.00	0.13	0.37	0.04	0.47	1.00	0.01	0.99	1.00
Non-profit institutions serving households	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00
Government education services	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00
Government health services	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00
Other federal government services	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00
Other provincial and territorial government services	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00
Other municipal government services	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00
Other aboriginal government services	0.40	0.49	0.11	1.00	0.13	0.61	0.03	0.23	1.00	0.01	0.99	1.00

Table 2-A-2. Population coefficients used to disaggregate and downscale provincial final demand into the hydro-economic regions in the Saskatchewan River Basin.

Province	Alberta (AB)				Saskatchewan (SK)					Manitoba (MB)		
Hydro-Economic Region	NSRB	SSRB	RST	AB	NSRB	SSRB	SRB	RST	SK	SRB	RST	MB
Population coefficient	0.39	0.51	0.10	1.00	0.14	0.31	0.04	0.51	1.00	0.01	0.99	1.00

2-A-2. Spatially disaggregated provincial IO tables

In the matrices below, the following abbreviations and notations are used: SK: Saskatchewan Province, AB: Alberta Province, MB: Manitoba Province, NS: North Saskatchewan River Sub-basin, SS: South Saskatchewan River Sub-basin, S: Saskatchewan River Sub-basin, RST: Rest of the Province.

- Supply Tables:

$$\mathbf{V_{SK}} = \begin{bmatrix} \mathbf{V_{SK-NS}} & \mathbf{V_{SK-SS-NS}} & \mathbf{V_{SK-S-NS}} & \mathbf{V_{SK-RST-NS}} \\ \mathbf{V_{SK-NS-SS}} & \mathbf{V_{SK-SS}} & \mathbf{V_{SK-S-SS}} & \mathbf{V_{SK-RST-SS}} \\ \mathbf{V_{SK-NS-S}} & \mathbf{V_{SK-SS-S}} & \mathbf{V_{SK-S}} & \mathbf{V_{SK-RST-S}} \\ \mathbf{V_{SK-NS-RST}} & \mathbf{V_{SK-SS-RST}} & \mathbf{V_{SK-S-RST}} & \mathbf{V_{SK-RST}} \end{bmatrix}$$

$$\mathbf{V_{AB}} = \begin{bmatrix} \mathbf{V_{AB-NS}} & \mathbf{V_{AB-SS-NS}} & \mathbf{V_{AB-RST-NS}} \\ \mathbf{V_{AB-NS-SS}} & \mathbf{V_{AB-SS}} & \mathbf{V_{AB-RST-SS}} \\ \mathbf{V_{AB-NS-RST}} & \mathbf{V_{AB-SS-RST}} & \mathbf{V_{AB-RST}} \end{bmatrix}$$

$$\mathbf{V_{MB}} = \begin{bmatrix} \mathbf{V_{MB-S}} & \mathbf{V_{MB-RST-S}} \\ \mathbf{V_{MB-S-RST}} & \mathbf{V_{MB-RST}} \end{bmatrix}$$

where V_{SK}, V_{AB}, and V_{MB} are spatially disaggregated supply tables for Alberta, Saskatchewan, and Manitoba, respectively. $V_{P\text{-}Ri}$ is the supply table for region R_i in province P, and $V_{P\text{-}Ri\text{-}Rj}$ is the inter-regional supply table for regions R_i and R_j in province P. All supply tables are commodity-by-industry tables with a dimension of [66 × 35].

- Use tables:

$$\mathbf{U_{SK}} = \begin{bmatrix} \mathbf{U_{SK-NS}} & \mathbf{U_{SK-SS-NS}} & \mathbf{U_{SK-S-NS}} & \mathbf{U_{SK-RST-NS}} \\ \mathbf{U_{SK-NS-SS}} & \mathbf{U_{SK-SS}} & \mathbf{U_{SK-S-SS}} & \mathbf{U_{SK-RST-SS}} \\ \mathbf{U_{SK-NS-S}} & \mathbf{U_{SK-SS-S}} & \mathbf{U_{SK-S}} & \mathbf{U_{SK-RST-S}} \\ \mathbf{U_{SK-NS-RST}} & \mathbf{U_{SK-SS-RST}} & \mathbf{U_{SK-S-RST}} & \mathbf{U_{SK-RST}} \end{bmatrix}$$

$$\mathbf{U_{AB}} = \begin{bmatrix} \mathbf{U_{AB-NS}} & \mathbf{U_{AB-SS-NS}} & \mathbf{U_{AB-RST-NS}} \\ \mathbf{U_{AB-NS-SS}} & \mathbf{U_{AB-SS}} & \mathbf{U_{AB-RST-SS}} \\ \mathbf{U_{AB-NS-RST}} & \mathbf{U_{AB-SS-RST}} & \mathbf{U_{AB-RST}} \end{bmatrix}$$

$$\mathbf{U_{MB}} = \begin{bmatrix} \mathbf{U_{MB-S}} & \mathbf{U_{MB-RST-S}} \\ \mathbf{U_{MB-S-RST}} & \mathbf{U_{MB-RST}} \end{bmatrix}$$

Where U_{SK}, U_{AB}, and U_{MB} are spatially disaggregated use tables for Alberta, Saskatchewan, and Manitoba, respectively. $U_{P\text{-}R_i}$ is the use table for region R_i in province P, and $U_{P\text{-}R_i\text{-}R_j}$ is the inter-regional use table for regions R_i and R_j in province P. All use tables are also commodity-by-industry tables with a dimension of [66 × 35].

Table 2-A-3, Table 2-A-4 in this Annex show examples of spatially disaggregated provincial supply and use tables created in this study for Manitoba. The sub-matrices that are shown above in the V_{MB} and U_{MB} are presented in these tables by different shades: green for the regional matrices (i.e., $V_{MB\text{-}S}$, $V_{MB\text{-}RST}$ and $U_{MB\text{-}S}$, $U_{MB\text{-}RST}$) and yellow for the inter-regional matrices (i.e., $V_{MB\text{-}S\text{-}RST}$, $V_{MB\text{-}RST\text{-}S}$ and $U_{MB\text{-}S\text{-}RST}$, $U_{MB\text{-}RST\text{-}S}$). Due to the large dimensions of these matrices and for illustration purposes, not all but only some industries and commodities are shown in these tables.

Table 2-A-3. Example of spatially disaggregated provincial supply tables: the disaggregated supply table of Manitoba.

	Industry Commodity	1	2	3	4	5	6	7	…	35	1	2	3	4	5	6	7	…	35
		Irrigated-Crop and animal production BS11A	Rainfed-Crop and animal production BS11A	Forestry and logging BS113	Fishing, hunting and trapping BS114	Support activities for agriculture and forestry BS115	Mining, quarrying, and oil and gas extraction BS210	Utilities BS220	(Other sectors)	Other aboriginal government services GS914	Irrigated-Crop and animal production BS11A	Rainfed-Crop and animal production BS11A	Forestry and logging BS113	Fishing, hunting and trapping BS114	Support activities for agriculture and forestry BS115	Mining, quarrying, and oil and gas extraction BS210	Utilities BS220	(Other sectors)	Other aboriginal government services GS914
1	Grains and other crop products M111B	0.54	19.22	0.00	0.00	0.00	0.00	0.00	…	0.00	1.21	42.67	0.00	0.00	0.00	0.00	0.00	…	0.00
2	Live animals M112A	0.40	14.03	0.00	0.00	0.00	0.00	0.00		0.00	0.88	31.15	0.00	0.00	0.00	0.00	0.00		0.00
3	Other farm products M11D0	0.16	5.71	0.01	0.03	0.00	0.00	0.00		0.00	0.36	12.67	0.02	0.06	0.00	0.00	0.00		0.00
4	Forestry products and services M11E0	0.00	0.01	0.47	0.00	0.00	0.00	0.00		0.00	0.00	0.02	1.04	0.00	0.00	0.00	0.00		0.00
5	Fish, crustaceans, shellfish and other fishery products M1140	0.00	0.00	0.00	0.16	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.00		0.00
6	Support services related to farming and forestry M1150	0.03	1.11	0.01	0.00	0.72	0.00	0.00		0.00	0.07	2.47	0.01	0.00	1.59	0.00	0.00		0.00
7	Mineral fuels M21B0	0.00	0.00	0.00	0.00	0.00	11.75	0.00		0.00	0.00	0.00	0.00	0.00	0.00	26.08	0.00		0.00
…	(Other Commodities)	…	…	…	… $V_{MB\text{-}S}$	…	…	…		…	…	…	…	… $V_{MB\text{-}RST\text{-}S}$	…	…	…		…
66	Other aboriginal government services G9140	0.00	0.00	0.00	0.00	0.00	0.00	0.00		5.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00		12.78
1	Grains and other crop products M111B	0.22	7.82	0.00	0.00	0.00	0.00	0.00	…	0.00	74.46	2634.29	0.00	0.00	0.00	0.00	0.00	…	0.00
2	Live animals M112A	0.16	5.71	0.00	0.00	0.00	0.00	0.00		0.00	54.35	1922.87	0.00	0.00	0.00	0.00	0.00		0.00
3	Other farm products M11D0	0.07	2.32	0.00	0.01	0.00	0.00	0.00		0.00	22.12	782.42	1.16	3.88	0.00	0.00	0.00		0.00
4	Forestry products and services M11E0	0.00	0.00	0.19	0.00	0.00	0.00	0.00		0.00	0.03	1.07	64.40	0.00	0.00	0.00	0.00		0.00
5	Fish, crustaceans, shellfish and other fishery products M1140	0.00	0.00	0.00	0.07	0.00	0.00	0.00		0.00	0.01	0.28	0.00	22.29	0.00	0.00	0.00		0.00
6	Support services related to farming and forestry M1150	0.01	0.45	0.00	0.00	0.29	0.00	0.00		0.00	4.31	152.65	0.82	0.00	98.19	0.00	0.00		0.00
7	Mineral fuels M21B0	0.00	0.00	0.00	0.00	0.00	4.78	0.00		0.00	0.00	0.00	0.00	0.00	0.00	1609.89	0.00		0.00
…	(Other Commodities)	…	…	…	… $V_{MB\text{-}S\text{-}RST}$	…	…	…		…	…	…	…	… $V_{MB\text{-}RST}$	…	…	…		…
66	Other aboriginal government services G9140	0.00	0.00	0.00	0.00	0.00	0.00	0.00		2.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00		789.02

Table 2-A-4. Example of spatially disaggregated provincial use tables: the disaggregated use table of Manitoba.

	Industry / Commodity	1	2	3	4	5	6	7	…	35	1	2	3	4	5	6	7	…	35
		Irrigated-Crop and animal production BS11A	Rainfed-Crop and animal production BS11A	Forestry and logging BS113	Fishing, hunting and trapping BS114	Support activities for agriculture and forestry BS115	Mining, quarrying, and oil and gas extraction BS210	Utilities BS220	(Other sectors)	Other aboriginal government services GS914	Irrigated-Crop and animal production BS11A	Rainfed-Crop and animal production BS11A	Forestry and logging BS113	Fishing, hunting and trapping BS114	Support activities for agriculture and forestry BS115	Mining, quarrying, and oil and gas extraction BS210	Utilities BS220	(Other sectors)	Other aboriginal government services GS914
1	Grains and other crop products M111B	0.052	1.838	0.000	0.000	0.000	0.000	0.000	…	0.00	0.062	2.193	0.000	0.000	0.000	0.000	0.000	…	0.000
2	Live animals M112A	0.024	0.841	0.000	0.000	0.000	0.000	0.000		0.00	0.028	1.003	0.000	0.000	0.000	0.000	0.000		0.000
3	Other farm products M11D0	0.081	2.875	0.005	0.000	0.000	0.000	0.000		0.00	0.097	3.428	0.006	0.000	0.000	0.000	0.000		0.000
4	Forestry products and services M11E0	0.000	0.000	0.014	0.000	0.000	0.000	0.000		0.00	0.000	0.000	0.016	0.000	0.000	0.000	0.000		0.001
5	Fish, crustaceans, shellfish and other fishery products M1140	0.000	0.000	0.000	0.002	0.000	0.000	0.000		0.00	0.000	0.000	0.000	0.003	0.000	0.000	0.000		0.000
6	Support services related to farming and forestry M1150	0.048	1.707	0.080	0.000	0.000	0.000	0.000		0.00	0.058	2.035	0.095	0.000	0.000	0.000	0.000		0.000
7	Mineral fuels M21B0	0.006	0.205	0.001	0.000	0.001	0.149	0.553		0.02	0.007	0.244	0.001	0.000	0.001	0.178	0.104		0.021
…	(Other Commodities)	…	…	…	…	… $U_{MB\text{-}S}$	…	…		…	…	…	…	…	… $U_{MB\text{-}RST\text{-}S}$	…	…		…
66	Other aboriginal government services G9140	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000
1	Grains and other crop products M111B	0.016	0.574	0.000	0.000	0.000	0.000	0.000	…	0.0000	6.689	236.621	0.000	0.006	0.000	0.000	0.000	…	0.000
2	Live animals M112A	0.007	0.263	0.000	0.000	0.000	0.000	0.000		0.0000	3.060	108.275	0.000	0.000	0.000	0.000	0.000		0.000
3	Other farm products M11D0	0.025	0.897	0.001	0.000	0.000	0.000	0.000		0.0000	10.458	369.996	0.610	0.000	0.000	0.000	0.000		0.000
4	Forestry products and services M11E0	0.000	0.000	0.004	0.000	0.000	0.000	0.000		0.0002	0.000	0.000	1.779	0.000	0.000	0.000	0.000		0.098
5	Fish, crustaceans, shellfish and other fishery products M1140	0.000	0.000	0.000	0.001	0.000	0.000	0.000		0.0000	0.000	0.012	0.000	0.309	0.000	0.000	0.000		0.000
6	Support services related to farming and forestry M1150	0.015	0.533	0.025	0.000	0.000	0.000	0.000		0.0000	6.209	219.665	10.299	0.000	0.000	0.000	0.000		0.000
7	Mineral fuels M21B0	0.002	0.064	0.000	0.000	0.000	0.047	0.173		0.0056	0.745	26.336	0.086	0.015	0.072	19.179	11.273		2.293
…	(Other Commodities)	…	…	…	…	… $U_{MB\text{-}S\text{-}RST}$	…	…		…	…	…	…	…	… $U_{MB\text{-}RST}$	…	…		…
66	Other aboriginal government services G9140	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000

2-A-3. Integrated IO tables for the Saskatchewan River Basin

- Supply Table:

$$\mathbf{V}_{\mathbf{Integrated}} = \begin{bmatrix} \mathbf{V}_{\mathbf{SK}} & \mathbf{V}_{\mathbf{AB-SK}} & \mathbf{V}_{\mathbf{MB-SK}} \\ \mathbf{V}_{\mathbf{SK-AB}} & \mathbf{V}_{\mathbf{AB}} & \mathbf{V}_{\mathbf{MB-AB}} \\ \mathbf{V}_{\mathbf{SK-MB}} & \mathbf{V}_{\mathbf{AB-MB}} & \mathbf{V}_{\mathbf{MB}} \end{bmatrix}$$

- Use Table:

$$\mathbf{U}_{\mathbf{Integrated}} = \begin{bmatrix} \mathbf{U}_{\mathbf{SK}} & \mathbf{U}_{\mathbf{AB-SK}} & \mathbf{U}_{\mathbf{MB-SK}} \\ \mathbf{U}_{\mathbf{SK-AB}} & \mathbf{U}_{\mathbf{AB}} & \mathbf{U}_{\mathbf{MB-AB}} \\ \mathbf{U}_{\mathbf{SK-MB}} & \mathbf{U}_{\mathbf{AB-MB}} & \mathbf{U}_{\mathbf{MB}} \end{bmatrix}$$

where $V_{Integrated}$ and $U_{Integrated}$ are the integrated supply and use tables for the entire Saskatchewan River Basin, respectively. V_{Pi} and U_{Pi} are supply and use tables for province i, $V_{Pi\text{-}Pj}$ and $U_{Pi\text{-}Pj}$ are inter-regional supply and use tables for provinces i and j.

Chapter 3

Testing the Reliability of Hydro-Economic Inter-Regional Supply-side Input-Output Models under Different Climatic Conditions in a Transboundary River Basin

Eamen, L., Brouwer, R., and Razavi, S. (Under Revision). Testing the Reliability of Hydro-Economic Inter-Regional Supply-side Input-Output Models under Different Climatic Conditions in a Transboundary River Basin.

Abstract

Conventional input-output (IO) models and their supply-side extensions with water inputs are developed based on economic data for a particular year. This raises the question of how reliable such hydro-economic models are in predicting the economic impacts under climatic conditions different from the model's base year. Although the temporal transferability of IO models has been examined before, no study has yet investigated the impacts of changing climatic conditions on the economic structure underlying hydro-economic IO-models. Here, we test the reliability of inter-regional supply-side input-output (ISIO) models under structural changes and varying climates in a transboundary water management context. Using the Saskatchewan River Basin in Western Canada as a case study, we develop four hydro-economic ISIO models based on economic and hydrological data from four years with different climate conditions, i.e., two dry and two wet years, which are one, two, four, and six years apart from each other. Having accounted for inflation over these years, our findings indicate that the impact of climatic conditions on economic output can be considerable. Further, the results show that each model performs well in predicting the economic output for the years whose climate conditions are similar to that of the model's base year. We

observe this temporal transferability of hydro-economic ISIO models even for the two years that are furthest apart (6 years), suggesting that the models remain reliable in predicting economic outputs for several years, as long as the climate conditions are within the range observed in the base years.

3.1. Introduction

The application of economic principles and modelling approaches in water resources management dates back to the 1960s (Harou et al., 2009). Economic methods and models have ever since been incorporated increasingly in water management studies related to water quality, water infrastructure development, and water allocation (e.g., Bielsa and Duarte, 2001; Cai et al., 2003; Gómez et al., 2004; Jenkins et al., 2004; Booker et al., 2005; Velázquez, 2006; Brouwer et al., 2008; Lenzen, 2009; Harou et al., 2010; Dellink et al., 2011; Ng et al., 2011; Blanco-Gutiérrez et al., 2013; Razavi et al., 2013; Asadzadeh et al., 2014; Graveline et al., 2014; Esteve et al., 2015; Kim and Kaluarachchi, 2016; Foster et al., 2017; MacEwan et al., 2017; Malek et al., 2018; Ridoutt et al., 2018; Häggmark Svensson and Elofsson, 2019; Dalcin and Fernandes Marques, 2020). One of these economic modelling approaches is the Input-Output (IO) model originally proposed by Leontief (1936; 1970). IO models quantify the inter-connectedness of sectors in an economy and relate the cross-sectoral flows of commodities to final demand in a certain accounting period (Miller and Blair, 2009).

The original IO model was extended to the supply-side IO model by Ghosh (1958) to accommodate the study of economic systems with limited resources. The IO modelling approach has been employed widely to evaluate the direct and indirect economic impacts of water-related changes, either qualitative or quantitative, at regional and inter-regional scales. These studies mostly use conventional IO models (e.g., Duarte et al., 2002; Kulshreshtha and Grant, 2003; Velázquez, 2006; Ewing et al., 2012; Cazcarro et al., 2013; López-Morales and Duchin, 2015; White et al., 2015; Lutter et al., 2016; Ridoutt et al., 2018), and only a limited number of studies have employed supply-side IO models (e.g., Yoo and Yang, 1999; González, 2011; Bogra et al., 2016).

IO models have been criticized as being static, reflecting the structure of an economy at a certain point in time, with no or very limited possibilities to account for endogenous technological innovation and change. IO models are developed based on statistical IO-tables (or supply and use tables) for a specific year. The structure of economies may, however, change over time due to a wide variety of internal and external drivers, including technological and price changes (Leontief et al., 1953; Leistritz and Murdock, 1981; Miller and Blair, 2009). Leontief (1970) presented "the dynamic inverse" to address the static nature of IO models, and this was applied or extended, among others, by Johnson (1985); Johnson (1986); Raa (1986); Sonis and Hewings (1998); Liew (2000); Okuyama et al. (2006); Jódar and Merello (2010). Other researchers examined whether an IO model based on economic data from a certain year can be used to reproduce sectoral production in other years (e.g., Leontief, 1941; Leontief, 1951; Leontief et al., 1953; Carter, 1970; Polenske, 1970; Beyers, 1972; Bezdek and Dunham, 1978; Midmore, 1993; de Mesnard, 2002), or investigated the temporal transferability and predictive power of conventional and supply-side IO models (e.g., Bon, 1986; Bon and Bing, 1993; Dietzenbacher and Hoen, 2006; Wood, 2011).

In addition to external shocks to demand and supply such as migration or a pandemic, changes in local and regional climatic conditions may also alter, temporarily or structurally, an economy's functioning and structure. Changes in climatic conditions are expected to affect especially climate-dependent activities, such as agriculture, forestry, hydropower, food processing, and commercial shipping. Since IO tables are developed for a specific year under particular climatic conditions in the past, the IO model will represent the economic behavior of agents and sectors in that economy under those particular climatic conditions. This raises the question of how reliable an IO model is in predicting the economic impacts of an exogenous change in water availability under climatic conditions different from the climate of the model's base year. This question becomes even more salient in a water resources management context at transboundary river basin scale where climatic conditions may vary differently in different parts of the basin (e.g., Levin-Koopman et al., 2015).

Changes in climatic conditions may impact the production of different water-dependent sectors in different ways and to different extents. The output of sectors such as irrigated and rain-fed agriculture may be affected directly by changes in water availability. Other sectors may be affected indirectly, however, by propagating these effects through the other sectors' purchases from those climate-dependent sectors. Given that the IO models are based on these crucial cross-sectoral linkages, they are well suited to assess the direct and indirect economic impacts of climatic changes. However, one needs to be mindful of the possible differences between climatic conditions and the economic structure of the model's base year and the year for which the economic impacts are projected. Moreover, supply and demand for the commodities produced by these economic activities are expected to change at the same time due to changes in associated price levels.

The present study aims to investigate and test the reliability of inter-regional supply-side IO (ISIO) models in predicting the economic response to changes in water intake under different climatic conditions. Here, we assess reliability by comparing the results of ISIO models based on economic and hydrological data across different years, when applied to predict the economic response to climatic conditions, represented by water availability here, different from the model's base year. Climate is defined by IPCC (2020) as the average weather over a period of time ranging from months to thousands of years. In this study, and particularly in this chapter, we use climate/climatic conditions to refer to water availability (precipitation and surface fresh water) in a certain year. To this end, an ISIO model adapted and contextualized to the hydrological boundaries of a transboundary river basin is used. The use of a hydrologically delineated IO model is advantageous over an aggregate IO model that adheres to administrative (provincial) boundaries because it is expected to be able to better represent possible differences in local water availability conditions. The ISIO is furthermore able to factor in freshwater availability constraints.

The ISIO models are developed for four years with dry and wet climates (two dry and two wet years) for the Saskatchewan River Basin (SaskRB) in Western Canada. The SaskRB is a large, multi-jurisdictional river basin encompassing three Canadian provinces with different economic structures. The scale of the river basin and the variation in the economic structures and climates across the sub-basins making up the SaskRB are expected to provide the appropriate testbed for examining the reliability of the models at different scales. This is the first study, to the best of our knowledge, which investigates the reliability and temporal transferability of ISIO models at the river-basin scale under different climatic conditions. The findings of this study provide insight into how reliable a river-basin based ISIO model is when applied under different climatic conditions.

In the remainder of this chapter, first, Section 3.2.1 describes our method to develop the ISIO models. Next, Section 3.2.2 explains the method of investigating structural economic changes underlying these models and defines how their predictive power is tested under different climates. Then, Section 3.3 presents the climatic and economic conditions of the SaskRB, followed by Section 3.4 presenting the results when analyzing structural changes in the developed ISIO models and testing their temporal transferability. Finally, Section 3.5 discusses the reliability of the ISIO models under different climatic conditions.

3.2. Methodology

3.2.1. Inter-regional Supply-side Input-Output Modelling

The methodology to develop an inter-regional supply-side Input-Output (ISIO) model as described in Chapter 2 is adopted and briefly summarized here. The emphasis in this chapter will be on testing the reliability of ISIO models under different climatic conditions over time, not the development of these models. Unlike conventional IO models, the ISIO model aims to investigate the relationship between sectoral output and value added in the case of limited resources, such as water (Ghosh, 1958). The ISIO model for an economy with n sectors is described in matrix notation as follows:

$$\mathbf{x} = (\mathbf{I} - \mathbf{B}^{\mathrm{T}})^{-1}\tilde{\mathbf{v}} \tag{3.1}$$

or $\mathbf{x} = \mathbf{G}\tilde{\mathbf{v}}$, where $\mathbf{x}$ is a vector of total sectoral production, $\mathbf{I}$ is a nxn identity matrix with ones on the main diagonal and zeros elsewhere, $\mathbf{B}$ is the matrix containing the so-called allocation coefficients in which elements b_{ij} represent the purchase amounts of sectors j from sector i as part of sector i's total output. $(\mathbf{I} - \mathbf{B}^{\mathrm{T}})^{-1} = \mathbf{G}$ is known as the output inverse, and $\tilde{\mathbf{v}}$ is the vector of sectoral value added. Note that in this chapter, bold uppercase letters are used to represent matrices, bold lowercase letters to indicate vectors, $^{-1}$ to indicate the matrix inversion operator, and $^{\mathrm{T}}$ to show the matrix transpose operator. Eq. (3.1) for rectangular or commodity-by-industry IO tables is presented as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{H}^{\mathrm{T}}\mathbf{C})^{-1}\tilde{\mathbf{v}} \tag{3.2}$$

where $\mathbf{H}^{\mathrm{T}}\mathbf{C}$ is an industry-by-industry (nxn) matrix that replaces $\mathbf{B}^{\mathrm{T}}$, and $(\mathbf{I} - \mathbf{H}^{\mathrm{T}}\mathbf{C})^{-1} = \mathbf{G}$. In commodity-by-industry IO tables, where each sector can produce more than one commodity, the (nxn) matrix of $\mathbf{H}^{\mathrm{T}}\mathbf{C}$ is created using the supply and use tables to replace the allocation coefficient matrix $\mathbf{B}^{\mathrm{T}}$. $\mathbf{H}$ is the result of dividing the use matrix by the total output of commodities (row sums of the supply matrix), and $\mathbf{C}$ is calculated by dividing the supply matrix by the total output of industries (column sums of the supply matrix).

Since publicly available IO tables are published at aggregated administrative levels, such as provinces in this case, the following spatial scaling process is applied to reconcile the economic data collected within the provincial boundaries with the water use data available within the hydrological boundaries of a river basin. The process consists of three main steps:

1- Create IO (supply and use) tables for each sub-basin by downscaling the provincial IO tables proportional to the labor force employed in different sectors found in the census dissemination areas located within each sub-basin. Census dissemination areas are defined by Statistics Canada (2018d) as the highest spatial resolution areas, at which all census data, including labor and population statistics are available.

2- Account for inter-sub-basin IO (supply and use) tables using intra- and inter-provincial trade flows, the labor force (supply), and population (use) data in the sub-basins in each province.

3- Re-assemble and upscale the downscaled provincial matrices to be able to apply the ISIO model at both river basin and provincial levels.

The ISIO model generated through the above downscaling and upscaling process includes a water component reflecting the amount of sectoral water use at sub-basin level. Water is included in this ISIO model as a productivity indicator, reflecting the amount of water needed to generate one unit of sectoral output. The value of change in the amount of water use (intake) is then estimated using $\Delta\mathbf{v}_{\mathrm{w}} = \mathbf{p}\Delta\mathbf{w}$, where $\Delta\mathbf{v}_{\mathrm{w}}$ is the value of change, $\mathbf{p}$ is the productivity (measured as sectoral monetary output per physical unit of water use), and $\Delta\mathbf{w}$ is the change in the amount of available water for sectoral use. Since water is assumed a primary input, this value of change is considered part of sectoral value added. Therefore, changes in sectoral gross output (i.e., final and intermediate output) due to changes in water availability, assuming that other value added components remain unchanged, is estimated as:

$$\Delta\mathbf{x} = \mathbf{G}\Delta\mathbf{v}_{\mathrm{w}} \tag{3.3}$$

A more detailed description of the model development and spatial up and downscaling procedures of the IO tables can be found in Chapter 2.

3.2.2. Measuring Structural Change and Testing the ISIO's Predictive Power

Inter-industry relationships in an economy evolve over time in response to various drivers, including alterations to demand, supply, prices, and/or technological progress (e.g., Tate, 1986; Okuyama et al., 2006). These changes in the structure of an economy over time can be represented by changes in the technical coefficient matrix of an IO model (Leontief 1951, 1953). Technical coefficients (a_{ij}), also known as direct input coefficients, equal the ratio of the inputs purchased by one sector from another sector to the total output of this former sector (Leontief, 1936; Miller & Blair, 2009):

$$a_{ij} = \frac{Input\ from\ sector\ i\ to\ sector\ j}{Output\ of\ sector\ j} \tag{3.4}$$

As the technical coefficient matrix of an economy with n sectors would contain n^2 technical coefficients a_{ij}. The comparison of these coefficients can take the form of a two-dimensional plot where technical coefficients of a previous year are shown on the x-axis, and technical coefficients of a later year on the y-axis (e.g., Carter, 1970). Coefficients that fall along the 45-degree line in this plot remain unchanged between years, whereas coefficients that are located above (below) the 45-degree line indicate that they have increased (decreased) in value over time.

To test the predictive power of the ISIO model, the model in a specific year (the base year) with a particular climatic condition (i.e., certain amount of water intake for main water-use sectors and precipitation for rain-fed agriculture) is used to reproduce and estimate the gross output in another year (with either different or similar climatic conditions to that of the model's base year) using the water intake or water availability data of the latter year. For example, with the ISIO structure of the year y1 and the water intake data in year y2, we would have:

$$\hat{\mathbf{x}}_{(y2)} = \mathbf{G}_{y1}\tilde{\mathbf{v}}_{y2} \tag{3.5}$$

where $\hat{\mathbf{x}}_{(y2)}$ is the gross output that would be required from various sectors related to the value added in year y2, considering the economic structure in year y1. The resulting output will then be compared with the actually observed output in year y2, i.e., $\mathbf{x}_{obs(y2)}$, at both sectoral and regional level, to calculate the prediction error, $e_{Prd(y2)}$, as follows:

$$e_{Prd(y2)} = \frac{\left(\hat{\mathbf{x}}_{(y2)} - \mathbf{x}_{obs(y2)}\right)}{\mathbf{x}_{obs(y2)}} \tag{3.6}$$

In order to control for the impact of changes in price levels over time and make the IO data comparable across different years, all IO tables are converted into Canadian dollar values of the most recent year for which the ISIO models are developed (2015).

3.3. Saskatchewan River Basin: The Case Study

The method outlined in the previous section was applied to the Saskatchewan River Basin (SaskRB) in Western Canada to investigate the reliability of ISIO models in predicting the economic response of economic activities undertaken in this river basin under different climates. The Saskatchewan River originates from its headwaters in the Rocky Mountains in Alberta, flows through the prairies in Alberta and Saskatchewan, and drains into a lowland wetland delta in western Manitoba. As mentioned in Chapter 2, we consider each sub-basin within the three Canadian provinces as a hydro-economic region in the ISIO models. We refer to these regions as AB-NSRB (North Saskatchewan river in Alberta), AB-SSRB (South Saskatchewan river in Alberta), SK-NSRB (North Saskatchewan river in Saskatchewan), SK-SSRB (South Saskatchewan river in Saskatchewan), SK-SRB (Saskatchewan River in Saskatchewan), and MB-SRB (Saskatchewan River in Manitoba) (see Figure 3.1).

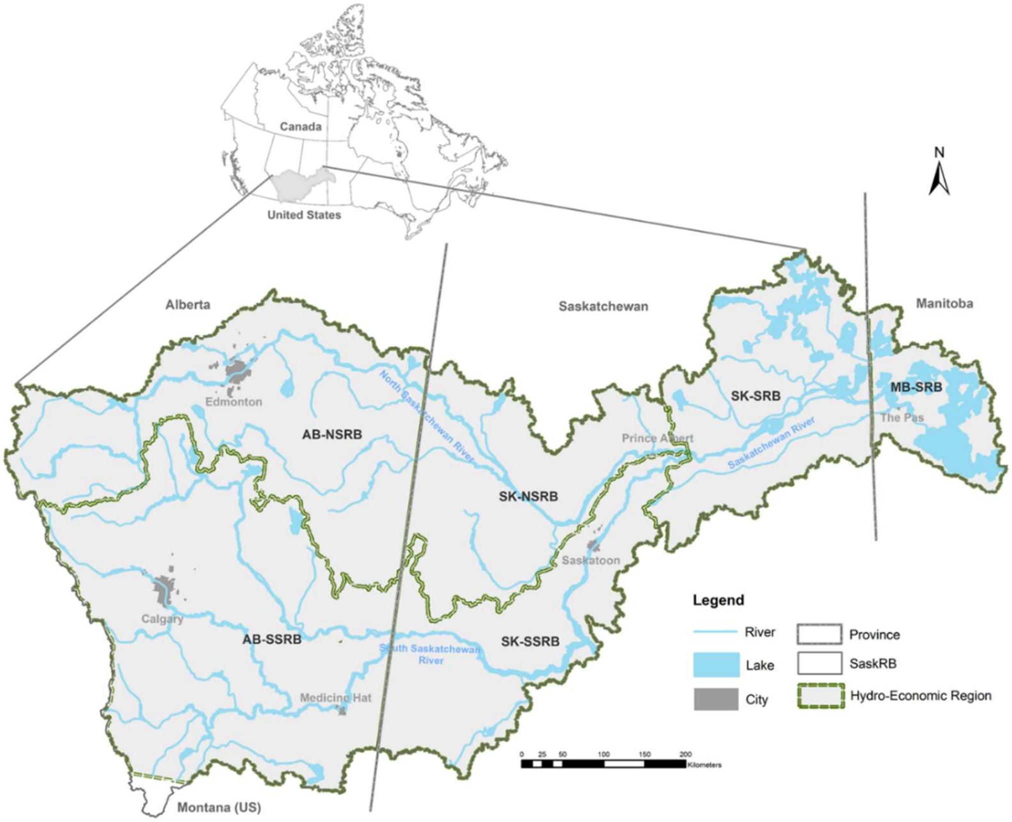


Figure 3.1. The location of the Saskatchewan River Basin in Canada and its six hydro-economic regions across the three provinces

These six regions are selected as the spatial study units of the SaskRB in this study. Since the Canadian IO tables are only available at provincial scale, these tables have to be downscaled and subsequently re-assembled to generate the ISIO models for these six regions and the entire SaskRB. In this study, the ISIO models for the years 2009 and 2015 are used to represent dry years, and 2013 and 2014 wet years. The spatial downscaling and upscaling procedure was developed in Chapter 2 for the year 2014 and was also applied for the ISIO models for 2009, 2013, and 2015.

The summary levels of the provincial IO tables for the years 2009, 2013, and 2015 from Statistics Canada (2018a and 2019a) were downscaled to the regions in each province using the Statistics Canada (2017a) labor force and population data, along with the available intra-provincial trade flow data (Statistics Canada, 2018e). The original IO tables at summary level consist of 35 industries and 66 commodities. The downscaled tables for the mentioned years were subsequently re-assembled to create the ISIO model for the entire SaskRB using the inter-provincial trade flow data (Statistics Canada, 2018a and 2019a). A Geographic Information System (GIS) data-frame was developed specifically for the SaskRB in an ArcGIS platform to conduct the associated spatial analysis, including the spatial down- and upscaling. To control for inflation and make the economic information comparable over different years, the IO tables were all converted to 2015 price levels, the most recent year for which IO tables were available at the time of this study, using the 2015 GDP deflator for each province (Statistics Canada, 2019b).

In this study, we used sectoral water use data published by Statistics Canada (2018f) in their "Physical Flow Account for Water Use". We obtained precipitation data during the crop season for the SaskRB from the Canadian Precipitation Analysis (CaPA) dataset (Mahfouf et al., 2007; Fortin et al., 2015; Fortin et al., 2018). The flow account data were used for the main water-use sectors, while precipitation data were used for the "Rain-fed crop and animal production" sector. The methodology for extracting the water use and precipitation data from the above data sources is explained in more detail in Chapter 2.

In order to investigate the reliability of the ISIO models in predicting the economic response of the sub-basins and the SaskRB as a whole to changes in water intake under different climatic conditions, we first examined the climatic and economic characteristics of the SaskRB in the selected years.

3.3.1. Climatic Conditions

The climatic conditions (water availability) for the four years under investigation (2009, 2013, 2014, and 2015) were examined by reviewing the summer precipitation (from May to September) levels across the SaskRB, and the annual flow levels of the South Saskatchewan River at Medicine Hat in Alberta and Saskatoon in Saskatchewan, and of the Saskatchewan River at The Pas in Manitoba (Figures 3.2 and 3.3). The pattern described below for the streamflow in these stations in the study years was also observed in stations in the North Saskatchewan River in both Alberta and Saskatchewan. The average annual flow is less likely to be appropriate to give a complete picture of the water availability in a certain year as the amount of precipitation might be lower than average in some months (e.g., cropping season) and higher than average in others. This is crucial particularly for sectors, such as agriculture, for which the timing of water availability is as important as its amount. Therefore, we considered summer precipitation here in addition to the annual streamflow to address this issue.

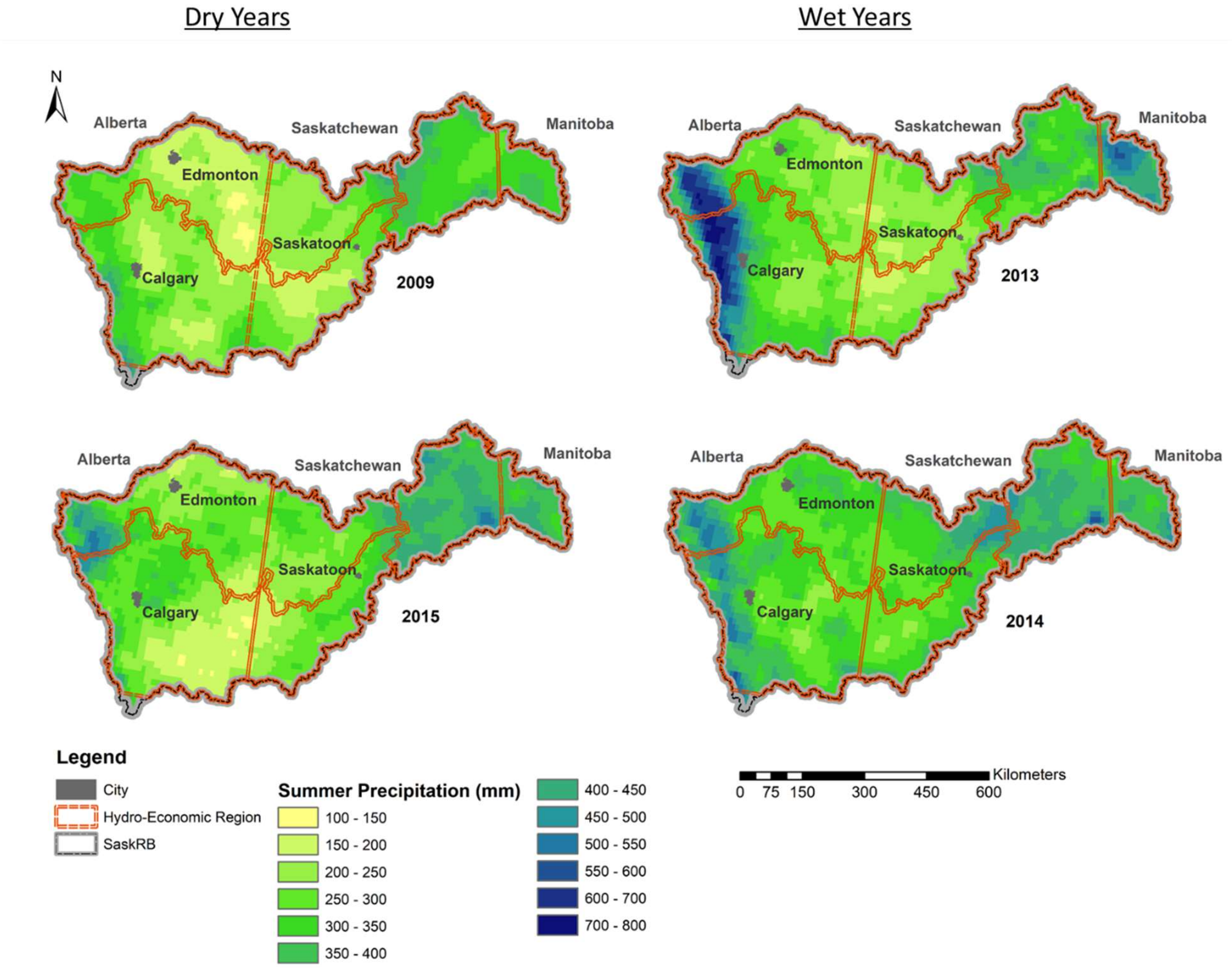


Figure 3.2. Summer precipitation in the Saskatchewan River Basin in the years 2009, 2013, 2014, and 2015

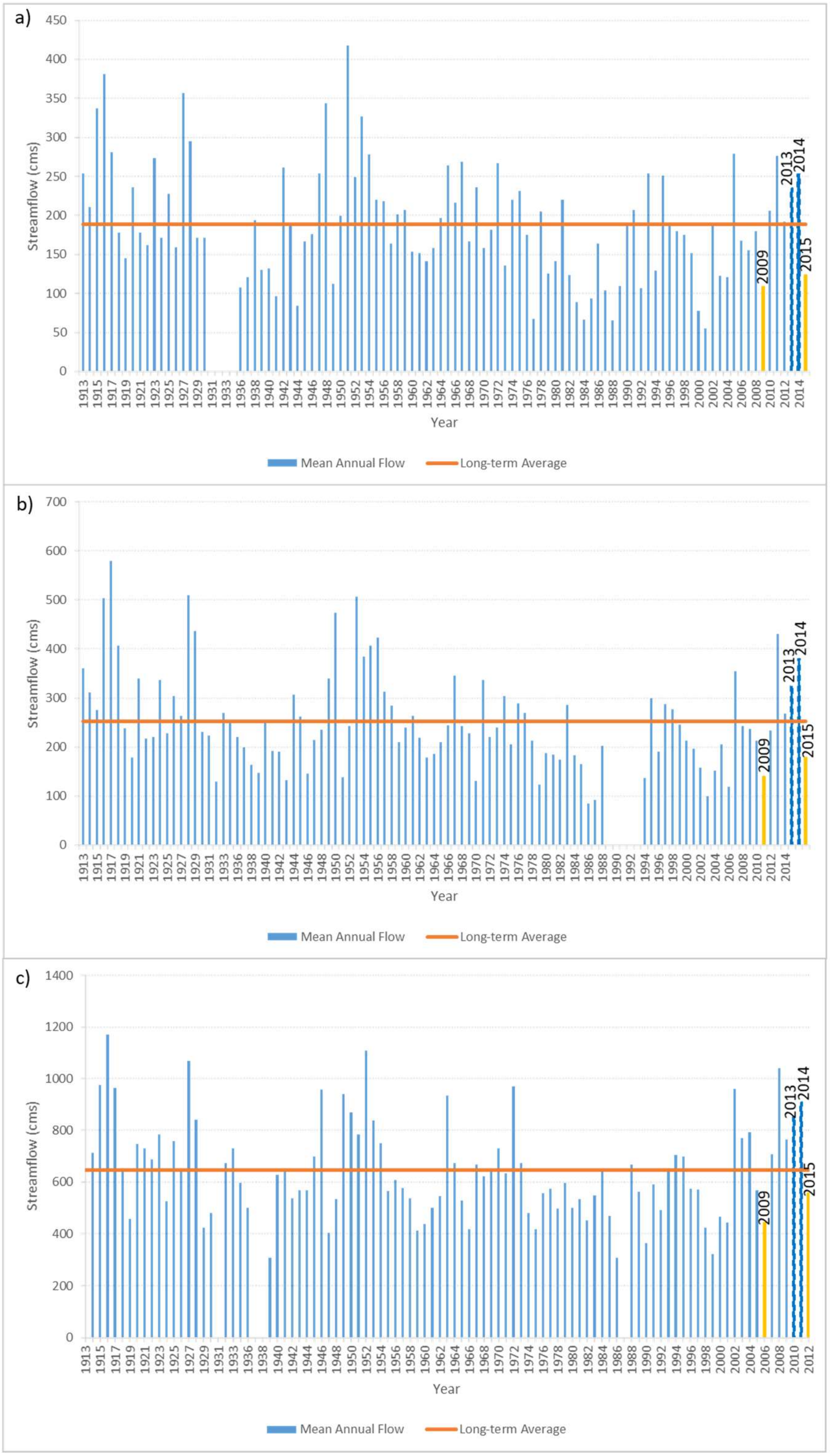


Figure 3.3. Annual flow and the long-term average flow over the period 1913-2015 of a) the South Saskatchewan River at Medicine Hat in Alberta, b) the South Saskatchewan River at Saskatoon in Saskatchewan, and c) the Saskatchewan River at The Pas in Manitoba

Based on the summer precipitation, 2009 was the driest year among the four years investigated in this study, with a range between 123 mm in the AB-NSRB and 546 mm in the AB-SSRB. The next driest year was 2015 with a summer precipitation varying from 140 mm in the AB-SSRB to 590 mm in the AB-NSRB (Figure 3.2). Table 3.1 presents the streamflow of the Saskatchewan River System in the four study years. As can be seen, The South Saskatchewan River in both Alberta and Saskatchewan and the Saskatchewan River in Manitoba also experienced a lower than average streamflow in these two years. The percentiles of the flow in these two years indicate that the years 2009 and 2015 were not extremely dry years.

The years 2013 and 2014 were wet according to both summer precipitation and river flow. Summer precipitation in the SaskRB ranged from 169 mm in SK-NSRB to 784 mm in AB-SSRB in 2013 and 225 to 580 mm in the AB-SSRB in 2014 (Figure 3.2). The streamflow in Alberta, Saskatchewan, and Manitoba was higher than average in these years (Table 3.1 and Figure 3.3). The flow percentiles presented in Table 3.1 show that the Saskatchewan River Basin did not experience extremely wet climate in either 2013 or 2014.

None of the years considered in this study were extremely wet or dry and were hence selected to represent more frequent wet and dry years. Under extreme climates, particular water management strategies might be adopted that differ from regular strategies taken under more frequent climatic conditions. The focus of this chapter is on analyzing the reliability of ISIO models under more frequent climates.

Table 3.1. Streamflow in the Saskatchewan River System in the study years based on statistics of the period 1913-2015

Province		**Alberta**	**Saskatchewan**	**Manitoba**
River		South Saskatchewan	South Saskatchewan	Saskatchewan
Station		Medicine Hat	Saskatoon	The Pas
Mean		189	253	645
Standard Deviation		72	98	186
2009	Flow (cms)	109	140	444
	Percentile	13	11	14
2013	Flow (cms)	235	325	851
	Percentile	75	80	84
2014	Flow (cms)	253	379	909
	Percentile	80	88	88
2015	Flow (cms)	124	178	556
	Percentile	20	20	34

3.3.2. Economic Characteristics

In this section, we review the economic structure of the three provinces sharing the SaskRB in the four years under investigation. Figure 3.4 shows the contribution of the three provinces to Canada's national gross domestic product (GDP) in the years 2009, 2013, 2014, and 2015 (Statistics Canada, 2018g). Total GDP in Canada over these four years increased from 1622 to 1857 billion Canadian dollars (in 2015 basic prices, i.e., market prices minus taxes and subsidies). Although GDP in Alberta, Saskatchewan, and Manitoba showed a similar overall trend in economic growth, Alberta and Saskatchewan experienced a negative growth between 2014 and 2015 (Table 3.2). As can be seen, Alberta's share in Canada's GDP over the four study years is more than four times larger than that of Saskatchewan and almost six times higher than the share of Manitoba.

Table 3.2 presents the gross value added generated by various sectors in the three provinces and the share of each sector in provincial GDP. Since we are primarily interested in investigating the interaction between water intake and economic output, the four main water-use sectors in the SaskRB are shown in Table 3.2: crop and animal production; mining, quarrying, and oil & gas extraction; utilities; and manufacturing. All the other sectors are merged into "Other Sectors". The crop and animal production sector is further disaggregated into irrigated and rain-fed crop and animal production in the ISIO models.

As can be seen in Table 3.2, GDP in constant 2015 price levels in Alberta and Saskatchewan was highest in 2014, followed by 2015, while GDP is slightly lower in 2014 than in 2015 in Manitoba. Among the three provinces, the share of "Crop and animal production" remained largely stable over the four years in Alberta and changed mostly in Saskatchewan from 10 percent in 2013 to 5.5 percent in 2014. The contribution of "Mining, quarrying, and oil and gas extraction" to provincial GDP decreased in both Alberta and Saskatchewan between 2014 and 2015 from 27 percent to 15 percent in Alberta and from 25 percent to 19 percent in Saskatchewan. This can partly be explained by the decline in the price of oil and potash in the second half of 2014. These prices remained low throughout 2015 and hence affected the potash and oil-related mining activities considerably, and ultimately resulted in a negative growth rate between 2014 and 2015 for both Alberta and Saskatchewan.

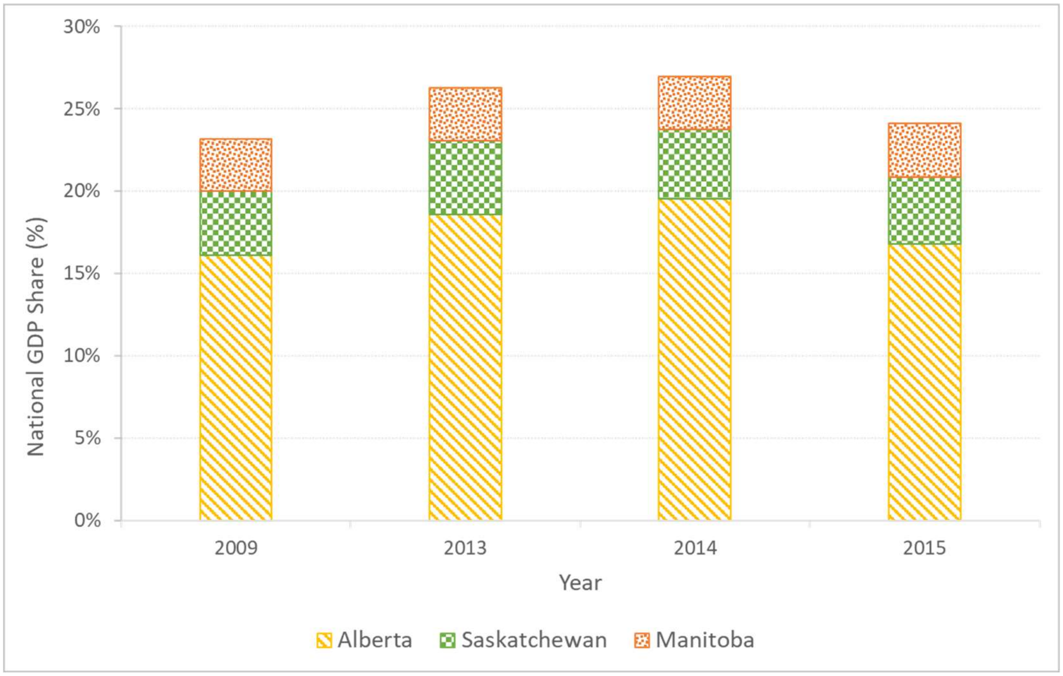


Figure 3.4. The share of Alberta, Saskatchewan, and Manitoba in Canada's GDP

Table 3.2. GDP in the three provinces making up the Saskatchewan River Basin and the share of each sector in provincial GDP over the years 2009, 2013, 2014 and 2015

Province	**Industry**	**GDP (billion CAD in 2015 prices)**				**Share in provincial GDP (%)**			
		2009 (dry)	2013 (wet)	2014 (wet)	2015 (dry)	2009 (dry)	2013 (wet)	2014 (wet)	2015 (dry)
Alberta	**Total of all industries**	249.54	307.50	326.20	311.91	100	100	100	100
	Crop and animal production	2.54	5.03	3.63	5.58	1.0	1.6	1.1	1.8
	Mining, quarrying, and oil and gas extraction	55.12	73.20	88.24	47.43	22.1	23.8	27.1	15.2
	Utilities	3.90	3.83	3.80	4.28	1.6	1.2	1.2	1.4
	Manufacturing	16.52	23.34	22.05	25.14	6.6	7.6	6.8	8.1
	Other sectors	171.47	202.10	208.47	229.48	68.7	65.7	63.9	73.6
Saskatchewan	**Total of all industries**	62.14	74.76	76.10	75.31	100	100	100	100
	Crop and animal production	4.54	7.33	4.22	6.78	7.3	9.8	5.5	9.0
	Mining, quarrying, and oil and gas extraction	13.90	18.08	19.09	14.13	22.4	24.2	25.1	18.8
	Utilities	1.25	1.49	1.52	1.68	2.0	2.0	2.0	2.2
	Manufacturing	4.25	4.62	4.58	4.30	6.8	6.2	6.0	5.7
	Other sectors	38.20	43.23	46.70	48.41	61.5	57.8	61.4	64.3
Manitoba	**Total of all industries**	53.22	59.24	60.31	60.96	100	100	100	100
	Crop and animal production	1.74	2.74	2.01	2.43	3.3	4.6	3.3	4.0
	Mining, quarrying, and oil and gas extraction	1.46	2.44	2.35	1.54	2.7	4.1	3.9	2.5
	Utilities	1.81	1.89	1.90	1.87	3.4	3.2	3.2	3.1
	Manufacturing	5.81	6.33	6.35	6.03	10.9	10.7	10.5	9.9
	Other sectors	42.41	45.84	47.70	49.09	79.7	77.4	79.1	80.5

3.4. Modelling Assumptions and Limitations

As mentioned earlier, the IO models are developed based on IO tables for a specific year without accounting for endogenous technological innovation and change, which may change the structure of economies (Leontief et al., 1953; Leistritz and Murdock, 1981; Miller and Blair, 2009). This puts a big question mark on the reliability of these models in predicting the economic impacts for other years. The present research tries to address this question by developing models for four years and testing their reliability in replicating each other's output. Not only changes in the economic structure from one year to another affect the performance of these models, but also varying water availabilities due to climatic conditions between the model's base year and the year for which the economic impacts are predicted may influence the results. As these different water availability conditions may influence predicted output under varying climatic conditions, if possible, a sensitivity analysis should be conducted to evaluate the economic impacts under different climate conditions using models based on years reflecting the range of climatic conditions (water availabilities) for which they were built.

Prices of the goods and services are assumed to remain constant in the ISIO models. This assumption might be violated in reality, particularly between the base year of the model and the time for which the model is applied to estimate the economic impacts. This assumption in addition to the static nature of these models make the IO models less appropriate for informing longer term forecasts. They give at most an indication of the expected short-term direct and indirect impacts of, for example, a policy intervention if that intervention would take place in a year with similar conditions to the specific year for which the IO model is built.

In testing the reliability of ISIO models under different climatic conditions here, two "wet" and two "dry" years were selected. These years were selected based on two considerations: first, not being an extremely wet/dry year, and secondly, availability of the economic and water intake data. Extremely wet/dry years were not selected here because under extreme climate conditions, exceptional water management strategies different from regular strategies in the river basin might be adopted, whereas this research was aimed at testing the reliability of the ISIO models under relatively more frequent climate conditions and water availability.

Summer precipitation is considered here in addition to the annual streamflow because the average annual flow is less likely to be appropriate to give a complete picture of the water availability in a certain year. The amount of precipitation might be lower than average in some months (e.g., cropping season) and higher than average in others. This is crucial, particularly for sectors, such as agriculture, for which both the timing and amount of water availability are important.

3.5. Results

In this section, we first present the analysis of any possible structural changes in the economy of the SaskRB across the four years by comparing technical coefficients over years. Small differences in technical coefficients would indicate that the models could be transferable in time, whereas large differences would undermine their transferability. Then, we test the predictive power of the ISIO models over different time periods by applying each model to replicate gross output in other years under different climatic conditions. The prediction error is calculated by comparing the predicted and observed gross outputs in each year at both the regional and sector levels.

3.4.1. Structural Changes in the Economy

In this section, possible structural changes in the economy of the SaskRB as a whole and the South Saskatchewan River Basin in Alberta and Saskatchewan (i.e., the AB-SSRB and SK-SSRB regions, respectively) more specifically are presented in more detail to illustrate the procedure. This is because the majority of water-use sectors are distributed in the South Saskatchewan River Basin. As mentioned, the years 2013 and 2015 are wet and dry years, respectively, immediately preceding and following the wet year 2014. Using these back-to-back years in the structural analysis is expected to minimize the possible impact of structural changes in the estimated models. By including the year 2009, possible structural changes over a longer time interval between two models covering years with similar climatic conditions, i.e., 2009 and 2015, can be analyzed. Technical coefficients of the main water-use sectors, including rain-fed crop and animal production, in the SaskRB and each region in the years 2013 and 2014 were compared, as two years with similar climatic conditions. This process was repeated for the years 2014 and 2015 as two years with different climatic conditions. In doing so, two-dimensional plots were generated in which the values of technical coefficients in the earlier year $(a_{ij})_{y1}$ are shown on the horizontal axis, and the values of technical coefficients in the later year $(a_{ij})_{y2}$ on the vertical axis.

The plots of technical coefficients for the main water-use sectors in the SaskRB, the AB-SSRB, and the SK-SSRB for different years are presented in Figure 3.5. The underlying numerical values of the technical coefficients are presented in Tables 3-A-1 to 3-A-3 in the Supporting Information. In Figure 3.5, only the coefficients that fall either above or below the 45-degree line, and hence differ between years, are labeled. The subscripts to the technical coefficients (a) refer to the sectors. For example, the sector "Irrigated crop and animal production" is labeled 1, and so a_{11} refers to intermediate deliveries within this specific sector (between two years). Deliveries between different sectors (between two years) are indicated by a_{ij}. For example, a_{51} represents the technical coefficient from "Manufacturing" to "Irrigated crop and animal production" between two years. This hence allows us to track changes in the structure of the economy in the SaskRB.

According to Figures 3.5 (a-1) to (c-1) for the entire SaskRB, the use of inputs from "Mining, quarrying, and oil and gas extraction" in "Utilities" and "Manufacturing" increased from 2013 to 2014, whereas this decreased from 2014 to 2015. The same pattern can be observed for the deliveries between the sectors "Rainfed crop and animal production" and "Irrigated crop and animal production". Over the period 2009-2015, deliveries between "Mining, quarrying, and oil and gas extraction" on the one hand and "Utilities" and "Manufacturing" on the other hand increased, while the use of inputs from "Rain-fed crop and animal production" in "Irrigated crop and animal production" remained unchanged.

In the AB-SSRB (Figures 3.5 (a-2) to (c-2)), the use of inputs from "Mining, quarrying, and oil and gas extraction" in "Utilities" and "Manufacturing" slightly increased in the period 2013-2014, while their use decreased considerably in the periods 2014-2015 and 2009-2015. The use of inputs from "Rain-fed crop and animal production" in "Irrigated crop and animal production" experienced an increase in the periods 2013-2014 and 2009-2015, while it decreased between 2014 and 2015.

In the SK-SSRB (Figures 3.5 (a-3) to (c-3)), deliveries between "Mining, quarrying, and oil and gas extraction" on the one hand and "Utilities" and "Manufacturing" on the other hand slightly increased between 2013 and 2014, whereas these deliveries decreased between 2014 and 2015. Over the period 2009-2015, the coefficients experienced an increase. The exchange of inputs from "Manufacturing" to "Irrigated crop and animal production" increased from 2013 to 2014, while this decreased in the periods 2014-2015 and 2009-2015. Finally, deliveries between "Rain-fed crop and animal production” and “Irrigated crop and animal production” increased from 2013 to 2014, decreased between 2014 and 2015, and stayed the same over the period 2009-2015.

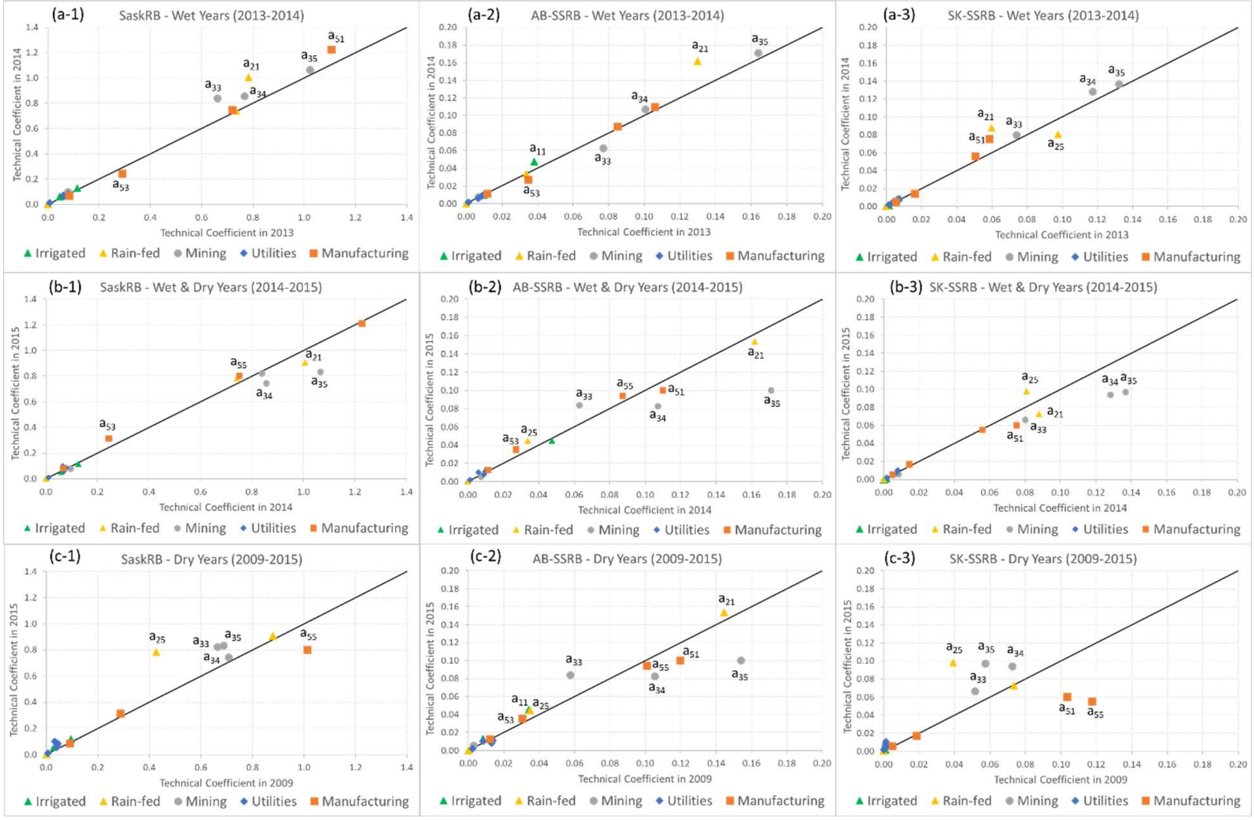


Figure 3.5. Technical coefficients (a_{ij}) of the main water-use sectors (ij) in (1) the Saskatchewan River Basin (SaskRB), (2) the South Saskatchewan River Basin in Alberta (AB-SSRB), and (3) the South Saskatchewan River Basin in Saskatchewan (SK-SSRB) between (a) two wet years, (b) a wet and a dry year, and (c) two dry years. Sector names are abbreviated for readability purposes. The coefficient a_{ij} sub-scripts ij refer to: 1=Irrigated: Irrigated crop and animal production; 2=Rain-fed: Rain-fed crop and animal production; 3=Mining: Mining, quarrying, and oil and gas extraction; 4=Utilities; 5=Manufacturing.

Overall, the water-use sectors “Mining, quarrying, and oil and gas extraction”, “Rain-fed crop and animal production”, and “Manufacturing” show the biggest changes in their technical coefficients over the years. The decrease in intermediate purchases between “Rain-fed crop and animal production” and “Irrigated crop and animal production” from 2014 to 2015 can partially be attributed to the dry climate in 2015 compared with the wet climate in 2014. As a result, the overall amount of gross output in rain-fed agriculture decreased, affecting the supply of commodities to irrigated agriculture. Furthermore, the decline in the price of oil and potash in the second half of 2014, which affected the output from the mining and oil industry, can be considered an external driver that caused a decrease in the intermediate deliveries from “Mining, quarrying, and oil and gas extraction” and to some extent from “Manufacturing” to other sectors between the years 2014 and 2015.

Summing up the results in this section, in addition to expected structural changes in the economy of the SaskRB over the longer 6-year time period between 2009 and 2015, changes in inter-industry relationships between years immediately following each other (i.e., 2013-2014 and 2014-2015) are observed that are not negligible, even after accounting for market distorions in market prices by using basic prices and accounting for inflation. Consequently, applying an ISIO model developed for a certain year to predict the economic conditions of the SaskRB in another year, even if those years are close together, may inevitably result in some degree of prediction errors. An important question is how large this prediction error is. Therefore, the reliability of these models will be tested further in the next section.

3.4.2. Economic Prediction Errors When Simulating Different Climatic Conditions

To test the predictive power of the ISIO models over time, the ISIO models for the four years were applied using the water intake data of other years under different climatic conditions. For example, the ISIO model based on the economic transactions captured by the IO tables during the wet year 2014 was applied to predict the output of the years 2009 (a dry year), 2013 (a wet year), and 2015 (a dry year) using the water intake data (including precipitation for rain-fed agriculture) of these three years. The predicted output in each year at sectoral and regional level was subsequently compared with the observed data of the same year to calculate the relative prediction error according to Eq. (3.6).

In this section, we first examine the transferability of ISIO models over a time period of six years by comparing the performance of the 2009 and 2015 ISIO models. Given that both 2009 and 2015 are dry years, in this comparison, we expect to observe primarily the impact of structural economic changes between the two years rather than the impacts of different climatic conditions. Then, we test the transferability of the ISIO models over a period of four years by comparing the performance of the 2009 and 2013 ISIO models. This comparison will capture both the impacts of different climatic conditions (2009 is a relatively dry year and 2013 a relatively wet year) and structural economic changes (economic growth in the SaskRB between 2009 and 2013 was 25%). Finally, we examine the transferability of the ISIO models over a period of one year for similar and different climatic conditions. In doing so, we compare the performance of the 2013 and 2014 ISIO models, as the models for two subsequent years with similar (wet) climates, and the 2014 and 2015 ISIO models, as the models for years under different climates (i.e., a wet year immediately followed by a dry year). The results of this comparative analysis help evaluate the influence of different temporal gaps, associated structural changes, and climatic conditions (water availability) on the predictive power of the developed ISIO models.

Regional errors in predicting gross output for different years using the four ISIO models of the SaskRB are presented in Figure 3.6. In this figure, the negative values indicate that gross output was underestimated, while the positive values indicate it was overestimated. The numerical values of the observed and simulated gross output at regional level for the SaskRB are presented in Tables 3-A-4 and 3-A-5 in the Supporting Information. The spatial distribution of the errors predicting the sectoral output of the main water-use sectors, including rain-fed crop and animal production, and the other sectors using the ISIO models for the four years is visualized in Figure 3.7. In the following sub-sections, the temporal transferability of the ISIO models as depicted in Figures 3.6 and 3.7 across years, sectors, and regions will be further elaborated.

3.4.2.1. Prediction Errors for Different Years

Figure 3.6 shows the prediction errors across years at river basin and regional scale. Starting with the results for the SaskRB as a whole, using ISIO models from previous years to predict (forecast) gross output of the SaskRB into the future, consistently results in an underestimation in all cases. Using ISIO models from the future years for back-casting purposes and simulating gross output in previous years results half of the time (in 3 of the 6 predictions) in an underestimation. It is hard to detect any systematic patterns in these results. Counter-intuitively perhaps since it was expected to be easier to predict a year in the past than in the future, the range of prediction errors when forecasting gross output is smaller (1-15% in absolute terms) than back-casting gross output (4-41% in absolute terms) for the whole SaskRB.

Both forecasting and back-casting over the longest time period (2009-2015) for two relatively dry years result in an underestimation of gross output. Predicting gross output in a future wet year using the ISIO model of a similar previous wet year (2013-2014) also results in an underestimation. However, the other way around, back-casting gross output in 2013 based on the estimated 2014 ISIO model yields an overestimation of gross output. Interestingly, back-casting based on the 2015 ISIO model for a relatively dry year to the relatively wet years 2013 and 2014 yields a higher than actually observed gross output, whereas forecasting the output in the relatively dry year 2015 using the ISIO models based on the wet years 2013 and 2014 produces a lower than observed gross output.

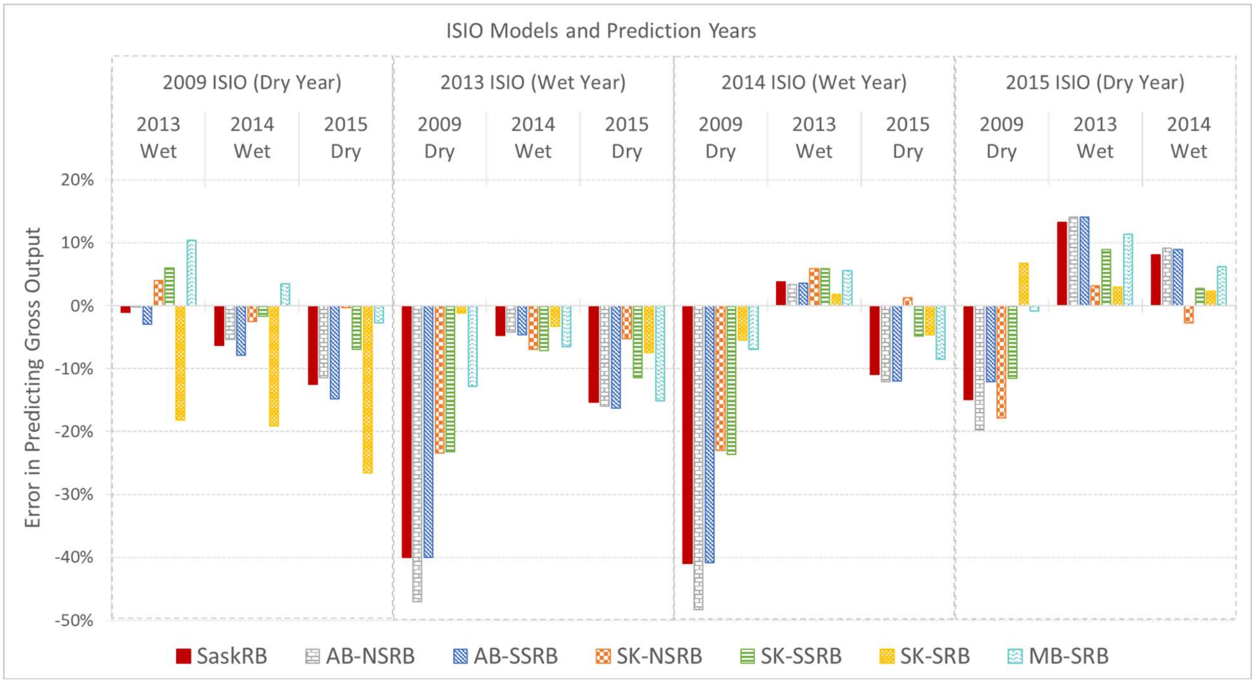


Figure 3.6. Regional errors in predicting the gross output across different years using the ISIO models for the years 2009, 2013, 2014, and 2015 in the Saskatchewan River Basin

In absolute terms, relatively small prediction errors are achieved when using the back-to-back ISIO models for the wet years 2013 and 2014 to estimate gross output. Predicting gross output for the SaskRB as a whole in 2014 based on the 2013 model yields a prediction error of 5 percent and vice versa 4 percent (Figure 3.6). Although this prediction error triples when transferring the economic structures captured by the dry 2009 and 2015 ISIO models over the corresponding six years, it does not exceed 15 percent (i.e., 12.5% when predicting gross output for SaskRB in 2015 based on 2009 and 14.9% when estimating gross output in 2009 based on 2015). The largest prediction errors (around 40%) occur when trying to predict gross output over a time period of four to five years in the dry year 2009 based on the two wet years 2013 and 2014. This may be due to both structural economic changes and changes in climate conditions. Forecasting and back-casting gross output between wet and dry years over a shorter time period of one to two years yields much lower errors between 8 and 15 percent, possibly because structural economic changes are less pronounced over this shorter time period.

These results are more or less in line with those obtained when using the full provincial IO models based on administrative boundaries for Alberta, Saskatchewan, and Manitoba, both in terms of direction (over- or under-estimation) and magnitude of the prediction errors. The results for the provincial models are included in Tables 3-A-6 and 3-A-7 in the Supporting Information to this chapter. This suggests that downscaling the provincial IO tables to river basin scale does not affect their performance in predicting gross output. Notable is that prediction errors at the SaskRB scale are especially consistent with the errors in predicting the output for Alberta, which can be attributed to the dominant role of this province in the economy of the SaskRB. Most of the output of the SaskRB in 2015 (87%) is produced in Alberta.

However, at a spatially further downscaled level, the results suggest that the predictive power of the ISIO models is quite different in some of the underlying hydro-economic regions. Before we discuss the prediction errors at a lower downscaled scale in detail, we first explore if they differ across the main water-use sectors and the other sectors in the next section.

3.4.2.2. Prediction Errors for Different Years and Sectors

The spatial distribution of the prediction errors of gross output using the four ISIO models across the main water users and the other sectors is presented in Figure 3.7. As shown in the previous section, most prediction errors (i.e., 63%) involve underestimations and most areas in Figure 3.7 are therefore red colored. The smallest absolute prediction error for the water-use sectors is 0.04 percent and found in Saskatchewan (SK-SSRB), while the largest absolute error for the water-use sectors is 39 percent in Alberta (AB-SSRB). For the other, non-water use sectors the range of prediction errors is slightly larger, varying between 0.2 percent in Saskatchewan (SK-SRB) and 58 percent in Alberta (AB-NSRB).

The four ISIO models predict the output of the water-use sectors with higher errors than the output of the other sectors 50 percent of the time (see also Table 3-A-8 in the Supporting Information). Hence, no systematic difference can be detected in the results for these two sectors. Examining the results of the ISIO models for dry years (i.e., 2009 and 2015), however, indicates that these models predict the output of the water-use sectors with larger absolute errors than the output of the other sectors 64 percent of the time (23 of the 36 predictions). The ISIO models for the wet years perform better in predicting the output of the water-use sectors than the output of the other sectors.

The largest errors in predicting the output of both the water-use sectors and the other sectors result from applying ISIO models for years with climate conditions different from that of the years for which the output is predicted. In the case of the water-use sectors, the largest errors are underestimations (-33% and -39%) when using the ISIO models for the wet years 2013 and 2014 and applying these to the dry year 2009 (in AB-SSRB). The largest errors in predicting the output of the other sectors are also underestimations (-53% and -58%) by the ISIO models for the wet years when applied to the dry year 2009 (in AB-NSRB). These prediction errors for the two different types of sectors are shown in Figure 3.7.

No consistent patterns can be observed when applying the ISIO models to similar climates. The smallest prediction errors are found when using the ISIO models for the two back-to-back wet years 2013 and 2014 to predict each other's output, but this is not the case for the ISIO models for the dry years. This may be due to the longer time period between the two dry years. As can be seen in Figure 3.7, the highest absolute prediction error for the wet years based on the ISIO models for the years 2013 and 2014 is 8.1 percent (in SK-NSRB). However, these errors range from 0.2 percent (in AB-NSRB and SK-SRB) to 29 percent (in SK-SRB) when applying the ISIO models for the dry years to predict the output of the water-use and other sectors in 2009 and 2015.

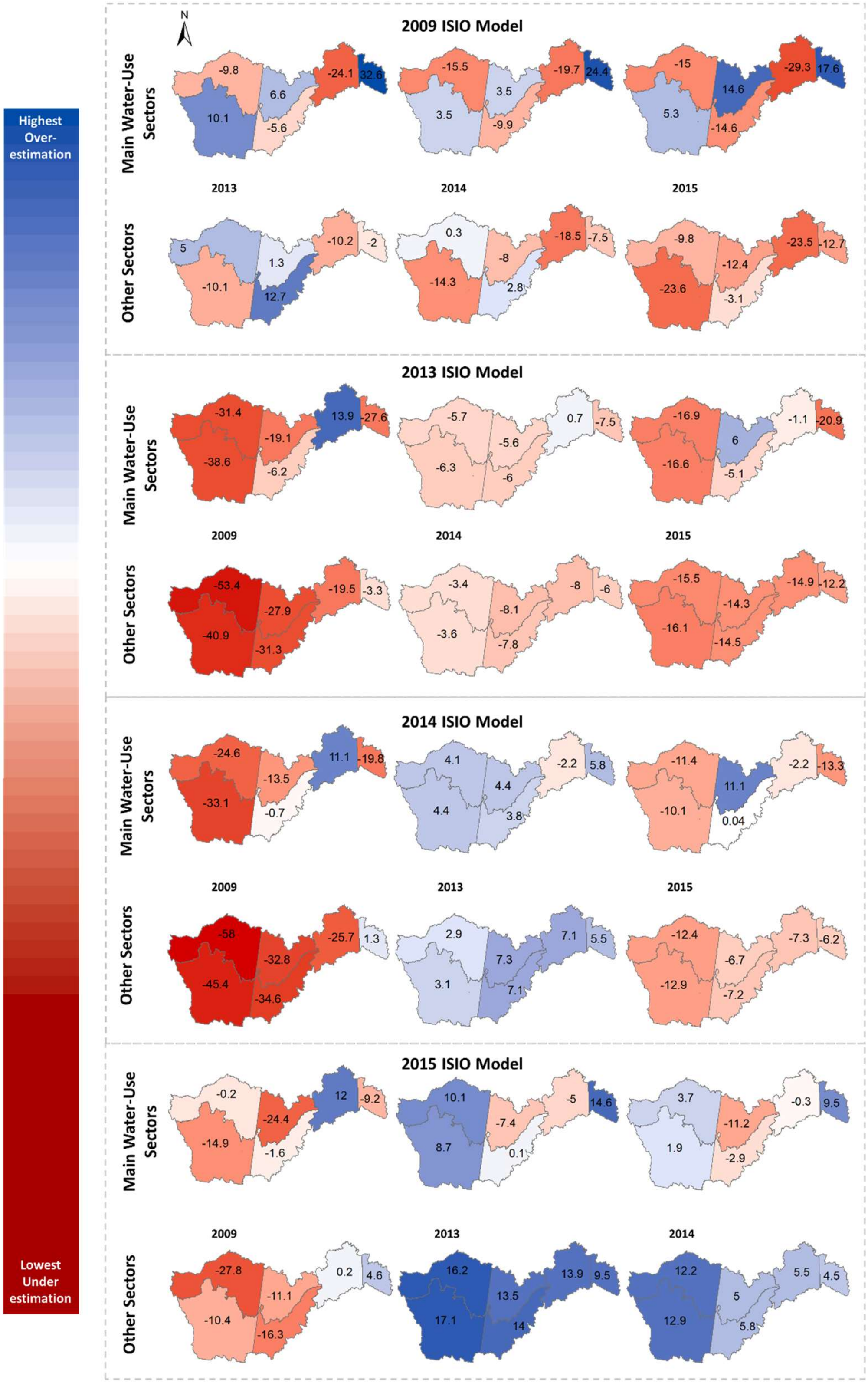


Figure 3.7. The spatial distribution of errors when predicting the output of the four main water-use sectors and the other sectors for different years using the 2009, 2013, 2014, and 2015 ISIO models

3.4.2.3. Prediction Errors for Different Years and Regions

Contrary to the finding that the river basin ISIO models perform more or less the same as the provincial IO models (Section 3.4.2.1), the performance of the ISIO models in predicting gross output at regional scale does not always sit well with the performance at river basin scale. For example, although the absolute prediction error for the year 2009 based on the 2014 ISIO model is 41 percent for the whole SaskRB, gross output of the downstream regions SK-SRB and MB-SRB are predicted with considerably lower absolute errors of 5 and 7 percent, respectively (Figure 3.6). As another example, the prediction error for the SK-SRB region in 2013 based on the 2009 ISIO model is 18 percent, whereas the prediction error for the SaskRB as a whole in the same year is only 1 percent. The spatial distribution of the prediction errors across the six regions does not show a clear overall pattern, except for the output prediction errors of the water-use sectors in Manitoba (MB-SRB). The latter are larger than the prediction errors for the other sectors under all ISIO models (Figure 3.7). This is possibly related to the small size of the economy captured in this downstream part of the river basin. Hence, whereas the results for the Alberta part in the SaskRB (where 89 percent of the province of Alberta's gross output is generated) are consistent with the overall prediction errors at river basin scale, the prediction errors for Manitoba's gross output in the SaskRB (1% of Manitoba's total gross output) are mostly inconsistent with the river basin errors.

Most ISIO model applications yield mixed results for different regions. For example, the prediction errors in AB-NSRB are higher for the water-use sectors than the other sectors based on the 2009 ISIO model, these errors are lower than the other sectors' errors when applying the 2015 ISIO model, and are a mixture of both based on the predictions using the 2013 and 2014 ISIO models. Nevertheless, some patterns can be found in particular parts of the results. For instance, applying the ISIO models back-to-back for the wet years results in larger absolute errors in predicting the output of the other sectors in Saskatchewan and the output of the water-use sectors in Alberta and Manitoba. These errors, however, do not exceed 8 percent. The models for the two wet years also predict the output of the other sectors for the dry year 2009 with larger absolute errors in all regions except for the MB-SRB, where the prediction error for the water-use sector is larger under all predictions.

3.6. Discussion and Conclusions

The main objective of this study was to develop ISIO models for the transboundary Saskatchewan River Basin in Canada for years facing different climatic conditions, and test the influence of these varying climatic conditions, manifesting themselves in changes in sectoral water intake and precipitation here, on the transferability of these models over shorter (1 year) and longer (4 to 6 years) time periods. Although previous studies have examined the impact of structural economic changes over time on the predictive power of supply-side IO models, this is the first study to investigate the potential impact of varying climatic conditions on model reliability, distinguishing between water-dependent and non-water dependent sectors at river basin and regional scale. It is important to note that we avoided choosing years with extreme climatic conditions, under which particular water management strategies might be adopted that would normally not be implemented in more regular dry or wet years.

Analyzing the changes in the structure of the economy in the SaskRB, we see that the technical coefficients of the SaskRB reflect the changes in the economic structure even over a short period of one year that the economic structure of the river basin slightly changes. This supports the findings presented in previous studies that show that the structural economic changes over time, even if they are gradual over a short period of time, are captured by the IO models (e.g., Leontief et al., 1953; Carter, 1970; Bezdek and Dunham, 1978; Midmore, 1993). According to these studies, the IO models remain reliable to predict the output for a number of years. These structural changes, however, affect the performance of the IO models in predicting the other years' gross output. This includes the intra- and inter-regional trade flows applied in creating the inter-regional supply-side IO models in this study. These trade flows change over time and affect the models' predictions (Beyers, 1972; Miller and Blair, 2009). Although we usually expect to observe technological innovations encapsulated in changing technical coefficients over longer time periods, more abrupt exogenous drivers such as price changes may influence the inter-industry relationships over shorter time periods. An example of such a driver in this study is the decline in the price of oil and potash in the second half of 2014 that partly explains the changes in deliveries between the "Mining, quarrying, and oil and gas extraction" sector and other sectors including "Manufacturing" in the SaskRB between 2014 and 2015. Additionally, our findings illustrate the impact of varying climatic conditions on the economic structure of the river basin in the short run as changes in deliveries between “Rain-fed crop and animal production” and “Irrigated crop and animal production” between 2014 and 2015 can be partially attributed to moving from wet to dry climate conditions during this time period.

The impact of different climatic conditions on the performance of (supply-side) IO models to reliably simulate and predict future gross output, especially in water-dependent sectors, has been neglected in the environmental economics literature. According to our results for the specific years involved, the ISIO models for the SaskRB seem to perform better in forecasting than back-casting gross output for the entire river basin. The ISIO models for the SaskRB furthermore seem to be able to reliably predict the economic output for years under similar climates. The performance of the hydro-economic models improves further over a shorter period of time where the structural economic changes remain relatively small (e.g., the two wet years 2013-2014). Nevertheless, our findings suggest that the influence of different climatic conditions on the transferability of the ISIO models is not negligible. This can be observed from the considerable errors when the ISIO models for wet years (2013 and 2014) are used to predict gross output for a dry year over a time period of four to five years (2009). The conclusion, therefore, is that if the ISIO models developed here are applied to years under different climatic conditions and over longer time periods, they generally generate higher prediction errors. Looking at the potential impact of varying climate on sectoral predictions, we observe that the ISIO models based on wet years predict the output of the water-use sectors more reliably at lower error than the models for dry years. This highlights the importance of considering the climatic conditions in evaluating the performance of these models in predicting the economic output for other years, in particular for climate dependent activities like agriculture. Although we expected no direct relationship between climate conditions and the predictions for other non-water use sectors, the ISIO models based on dry years nevertheless performed better in predicting the output of these sectors over different years.

The spatial scale and resolution are critically important in the reliability assessment of hydro-economic ISIO models that reflect different climatic conditions. The results in this study show a striking similarity at river basin and provincial scale, suggesting that the performance of the hydro-economic river basin models is not affected by the downscaling of the provincial IO tables in this specific case study. Not surprisingly, results at river basin scale are most consistent with the province that has the largest share in the economy of the river basin. However, prediction errors increase to almost 60 percent when zooming in further to regions with more detailed spatial and sectoral resolution. This seems in line with the findings by Leontief et al. (1953), Carter (1970), Bezdek and Dunham (1978), Bon (1986), Bon and Bing (1993) or Wood (2011), although none of these studies spatially downscaled IO tables to a finer spatial resolution or accounted for water intake in different sectors. For example, errors in predicting the output of different sectors in the U.S. economy using supply-side IO models between 1947 and 1977 reached 70 percent at sectoral level but did not exceed 16 percent at the total industry level (Bon, 1986). Another study by Bon and Bing (1993) testing the performance of supply-side IO models between 1963 and 1984 in the UK showed that the prediction errors reached 28 percent at sectoral level, but remained under 6 percent at the total industry level.

No systematic pattern can be detected in the spatial distribution of the prediction errors across the six regions. The uneven spatial distribution of the four ISIO models' prediction errors, particularly in predicting the output for years under different climates and with longer time gaps, is partly explained by measurement errors and the limited availability of reliable economic and water intake data for different years at more detailed spatial scales. This potential source of error especially manifests itself in regions with less data availability, i.e., either smaller regions (e.g., SK-SRB and MB-SRB) or regions with a lower concentration of economic activities (e.g., NSRB). Moreover, the 2009 IO tables include some data discrepancies due to regional confidentiality issues, also contributing to higher prediction errors that are unevenly distributed across the various regions using different ISIO models to predict gross output for years other than the models' base year.

Finally, despite the various limitations of (supply-side) IO models as described in the literature, in particular their static nature and the lack of an endogenous market-clearing mechanism in the economic structure in these models (e.g., determining the optimal allocation of scarce resources based on price signals and shifts in demand and supply), they provide invaluable insight into analyzing the direct and indirect short-term economic impacts of climate change and water policy on water-use sectors and other sectors operating in the economy of river basins. Their reliability to evaluate these impacts depends on their ability to simulate economic production and consumption under different climate conditions, as tested in this study. Comparing the annual ISIO models over time and varying climatic conditions provides insight into the dynamic structure underlying large-scale transboundary river basin economies. This study showed that by being mindful of associated prediction errors, especially at more detailed spatial resolution and over longer time periods with different climates, ISIO models can be applied as decision support tools in an integrated water resources management context, and inform sustainable water (re-)allocation strategies.

Author Contributions

LE developed the model, wrote the computer codes, designed and performed the experiments. LE and RB contributed to the interpretation of the results. LE wrote the paper. RB and SR commented on the manuscript and contributed to the editing of the paper.

Appendix 3-A: Supporting Information

Table 3-A-1. Technical coefficients of the Saskatchewan River Basin in 2009, 2013, 2014, and 2015

Year	(a_{ij})	Irrigated- Crop and animal production	Rain-fed- Crop and animal production	Mining, quarrying, and oil and gas extraction	Utilities	Manufacturing	Other sectors
2009	Irrigated- Crop and animal production	0.096	0.096	0.0001	0.00002	0.029	0.064
	Rain-fed- Crop and animal production	0.878	0.881	0.003	0.0002	0.427	0.649
	Mining, quarrying, and oil and gas extraction	0.042	0.042	0.664	0.707	0.689	2.580
	Utilities	0.042	0.042	0.033	0.006	0.045	0.674
	Manufacturing	1.687	1.688	0.287	0.091	1.013	14.743
	Other sectors	1.177	1.180	0.668	0.712	0.755	49.839
2013	Irrigated- Crop and animal production	0.115	0.115	0.0001	0.0001	0.046	0.177
	Rain-fed- Crop and animal production	0.783	0.783	0.001	0.001	0.735	1.094
	Mining, quarrying, and oil and gas extraction	0.078	0.078	0.662	0.767	1.022	2.703
	Utilities	0.060	0.060	0.063	0.008	0.077	1.805
	Manufacturing	1.106	1.106	0.290	0.083	0.720	13.756
	Other sectors	0.902	0.902	0.615	0.707	0.756	36.918
2014	Irrigated- Crop and animal production	0.125	0.125	0.00004	0.00004	0.059	0.092
	Rain-fed- Crop and animal production	1.006	1.006	0.0004	0.0004	0.741	0.843
	Mining, quarrying, and oil and gas extraction	0.095	0.095	0.839	0.855	1.065	3.044
	Utilities	0.069	0.069	0.064	0.010	0.078	1.759
	Manufacturing	1.227	1.227	0.244	0.067	0.750	12.903
	Other sectors	1.031	1.031	0.613	0.719	0.766	35.871
2015	Irrigated- Crop and animal production	0.115	0.115	0.0001	0.0001	0.056	0.092
	Rain-fed- Crop and animal production	0.904	0.904	0.0003	0.0003	0.783	0.857
	Mining, quarrying, and oil and gas extraction	0.080	0.080	0.822	0.744	0.833	2.326
	Utilities	0.059	0.059	0.100	0.011	0.085	1.827
	Manufacturing	1.211	1.211	0.314	0.083	0.803	12.675
	Other sectors	0.902	0.902	0.849	0.835	0.847	37.369

Table 3-A-2. Technical coefficients of the South Saskatchewan in Alberta (AB-SSRB) region in 2009, 2013, 2014, and 2015

Year	(a_{ij})	Irrigated-Crop and animal production	Rain-fed-Crop and animal production	Mining, quarrying, and oil and gas extraction	Utilities	Manufacturing	Other sectors
2009	Irrigated- Crop and animal production	0.034	0.034	0.00004	0.00001	0.008	0.012
	Rain-fed- Crop and animal production	0.144	0.144	0.0002	0.00003	0.035	0.051
	Mining, quarrying, and oil and gas extraction	0.003	0.003	0.057	0.105	0.154	0.285
	Utilities	0.013	0.013	0.008	0.002	0.014	0.135
	Manufacturing	0.120	0.120	0.031	0.012	0.101	1.237
	Other sectors	0.157	0.157	0.142	0.076	0.114	7.563
2013	Irrigated- Crop and animal production	0.038	0.038	0.00002	0.00002	0.010	0.027
	Rain-fed- Crop and animal production	0.130	0.130	0.0001	0.0001	0.034	0.091
	Mining, quarrying, and oil and gas extraction	0.007	0.007	0.077	0.101	0.164	0.348
	Utilities	0.009	0.009	0.007	0.001	0.010	0.145
	Manufacturing	0.106	0.106	0.035	0.012	0.085	1.220
	Other sectors	0.106	0.106	0.139	0.084	0.093	5.427
2014	Irrigated- Crop and animal production	0.047	0.047	0.00001	0.00002	0.010	0.035
	Rain-fed- Crop and animal production	0.162	0.162	0.00005	0.0001	0.034	0.119
	Mining, quarrying, and oil and gas extraction	0.007	0.007	0.063	0.107	0.171	0.353
	Utilities	0.009	0.009	0.006	0.001	0.010	0.143
	Manufacturing	0.110	0.110	0.027	0.012	0.087	1.228
	Other sectors	0.117	0.117	0.126	0.084	0.093	5.344
2015	Irrigated- Crop and animal production	0.045	0.045	0.00002	0.00002	0.013	0.034
	Rain-fed- Crop and animal production	0.153	0.153	0.0001	0.0001	0.045	0.116
	Mining, quarrying, and oil and gas extraction	0.006	0.006	0.084	0.083	0.100	0.281
	Utilities	0.008	0.008	0.010	0.002	0.011	0.142
	Manufacturing	0.100	0.100	0.035	0.013	0.094	1.166
	Other sectors	0.105	0.105	0.184	0.110	0.104	5.552

Table 3-A-3. Technical coefficients of the South Saskatchewan in Saskatchewan (SK-SSRB) region in 2009, 2013, 2014, and 2015

Year	(a_{ij})	Irrigated-Crop and animal production	Rain-fed-Crop and animal production	Mining, quarrying, and oil and gas extraction	Utilities	Manufacturing	Other sectors
2009	Irrigated- Crop and animal production	0.001	0.001	0.000002	0.0000002	0.001	0.001
	Rain-fed- Crop and animal production	0.073	0.074	0.0001	0.00001	0.039	0.066
	Mining, quarrying, and oil and gas extraction	0.001	0.001	0.051	0.072	0.057	0.184
	Utilities	0.001	0.001	0.001	0.0001	0.001	0.039
	Manufacturing	0.104	0.103	0.018	0.005	0.118	1.329
	Other sectors	0.153	0.153	0.064	0.037	0.103	7.597
2013	Irrigated- Crop and animal production	0.001	0.001	0.000001	0.000003	0.002	0.001
	Rain-fed- Crop and animal production	0.060	0.060	0.0001	0.0002	0.098	0.072
	Mining, quarrying, and oil and gas extraction	0.007	0.007	0.074	0.117	0.132	0.199
	Utilities	0.004	0.004	0.007	0.001	0.007	0.247
	Manufacturing	0.059	0.059	0.016	0.005	0.051	0.835
	Other sectors	0.081	0.081	0.054	0.049	0.087	4.517
2014	Irrigated- Crop and animal production	0.001	0.001	0.000001	0.000001	0.001	0.001
	Rain-fed- Crop and animal production	0.088	0.088	0.00004	0.0001	0.081	0.085
	Mining, quarrying, and oil and gas extraction	0.008	0.008	0.080	0.128	0.137	0.186
	Utilities	0.005	0.005	0.008	0.002	0.007	0.254
	Manufacturing	0.075	0.075	0.014	0.005	0.056	0.854
	Other sectors	0.104	0.104	0.055	0.048	0.092	4.425
2015	Irrigated- Crop and animal production	0.001	0.001	0.0000004	0.0000005	0.002	0.001
	Rain-fed- Crop and animal production	0.072	0.072	0.00003	0.00003	0.098	0.089
	Mining, quarrying, and oil and gas extraction	0.006	0.006	0.066	0.094	0.097	0.166
	Utilities	0.004	0.004	0.010	0.002	0.008	0.281
	Manufacturing	0.060	0.060	0.017	0.006	0.055	0.776
	Other sectors	0.085	0.085	0.067	0.053	0.094	4.545

Table 3-A-4. Predicted regional production for different years based on the ISIO models for the years 2009 and 2013 and water intake in each year (in 2015 price levels)

2009 ISIO Model

Hydro-economic Region	Sector	Observed 2013	Predicted 2013	Error (%)	Observed 2014	Predicted 2014	Error (%)	Observed 2015	Predicted 2015	Error (%)
		Million CAD	Million CAD		Million CAD	Million CAD		Million CAD	Million CAD	
AB-NSRB	Water Use	76910	69380	-9.8	80314	67890	-15.5	69644	59207	-15.0
	Other	138690	145664	5.0	143533	144030	0.3	154019	138927	-9.8
	Total	**215600**	**215045**	**-0.3**	**223847**	**211920**	**-5.3**	**223663**	**198134**	**-11.4**
AB-SSRB	Water Use	104296	114858	10.1	109620	113463	3.5	92752	97654	5.3
	Other	189438	170232	-10.1	196194	168177	-14.3	211927	161823	-23.6
	Total	**293734**	**285091**	**-2.9**	**305814**	**281640**	**-7.9**	**304678**	**259477**	**-14.8**
SK-NSRB	Water Use	8747	9329	6.6	8756	9065	3.5	7945	9102	14.6
	Other	8956	9075	1.3	9697	8916	-8.0	9825	8604	-12.4
	Total	**17703**	**18404**	**4.0**	**18453**	**17982**	**-2.6**	**17770**	**17707**	**-0.4**
SK-SSRB	Water Use	18737	17681	-5.6	18868	17007	-9.9	17228	14708	-14.6
	Other	32261	36353	12.7	34836	35797	2.8	35553	34437	-3.1
	Total	**50998**	**54034**	**6.0**	**53704**	**52804**	**-1.7**	**52781**	**49145**	**-6.9**
SK-SRB	Water Use	2955	2244	-24.1	2873	2307	-19.7	2769	1959	-29.3
	Other	2174	1952	-10.2	2355	1919	-18.5	2383	1824	-23.5
	Total	**5129**	**4196**	**-18.2**	**5228**	**4226**	**-19.2**	**5152**	**3783**	**-26.6**
MB-SRB	Water Use	418	553	32.6	411	511	24.4	395	465	17.6
	Other	752	737	-2.0	785	726	-7.5	801	699	-12.7
	Total	**1169**	**1290**	**10.4**	**1196**	**1237**	**3.4**	**1196**	**1164**	**-2.7**
SaskRB		**584333**	**578060**	**-1.1**	**608242**	**569810**	**-6.3**	**605240**	**529410**	**-12.5**

2013 ISIO Model

Hydro-economic Region	Sector	Observed 2009	Predicted 2009	Error (%)	Observed 2014	Predicted 2014	Error (%)	Observed 2015	Predicted 2015	Error (%)
		Million CAD	Million CAD		Million CAD	Million CAD		Million CAD	Million CAD	
AB-NSRB	Water Use	48651	33384	-31.4	80314	75723	-5.7	69644	57904	-16.9
	Other	119219	55541	-53.4	143533	138615	-3.4	154019	130160	-15.5
	Total	**167870**	**88925**	**-47.0**	**223847**	**214339**	**-4.2**	**223663**	**188063**	**-15.9**
AB-SSRB	Water Use	83225	51094	-38.6	109620	102736	-6.3	92752	77396	-16.6
	Other	140181	82887	-40.9	196194	189062	-3.6	211927	177745	-16.1
	Total	**223406**	**133981**	**-40.0**	**305814**	**291798**	**-4.6**	**304678**	**255141**	**-16.3**
SK-NSRB	Water Use	7541	6101	-19.1	8756	8267	-5.6	7945	8419	6.0
	Other	7387	5324	-27.9	9697	8908	-8.1	9825	8424	-14.3
	Total	**14928**	**11426**	**-23.5**	**18453**	**17175**	**-6.9**	**17770**	**16843**	**-5.2**
SK-SSRB	Water Use	14493	13595	-6.2	18868	17743	-6.0	17228	16341	-5.1
	Other	30483	20946	-31.3	34836	32102	-7.8	35553	30409	-14.5
	Total	**44976**	**34541**	**-23.2**	**53704**	**49845**	**-7.2**	**52781**	**46750**	**-11.4**
SK-SRB	Water Use	1939	2208	13.9	2873	2892	0.7	2769	2740	-1.1
	Other	1580	1272	-19.5	2355	2166	-8.0	2383	2029	-14.9
	Total	**3519**	**3480**	**-1.1**	**5228**	**5058**	**-3.2**	**5152**	**4768**	**-7.4**
MB-SRB	Water Use	432	313	-27.6	411	380	-7.5	395	313	-20.9
	Other	671	648	-3.3	785	738	-6.0	801	703	-12.2
	Total	**1103**	**961**	**-12.8**	**1196**	**1118**	**-6.5**	**1196**	**1016**	**-15.1**
SaskRB		**455802**	**273314**	**-40.0**	**608242**	**579334**	**-4.8**	**605240**	**512580**	**-15.3**

Table 3-A-5. Predicted regional production for different years based on the ISIO models for the years 2014 and 2015 and water intake in each year (in 2015 price levels)

2014 ISIO Model										
Hydro-economic Region	Sector	Observed 2009 Million CAD	Predicted 2009 Million CAD	Error (%)	Observed 2013 Million CAD	Predicted 2013 Million CAD	Error (%)	Observed 2015 Million CAD	Predicted 2015 Million CAD	Error (%)
AB-NSRB	Water Use	48651	36673	-24.6	76910	80081	4.1	69644	61701	-11.4
	Other	119219	50034	-58.0	138690	142711	2.9	154019	134866	-12.4
	Total	**167870**	**86707**	**-48.3**	**215600**	**222791**	**3.3**	**223663**	**196567**	**-12.1**
AB-SSRB	Water Use	83225	55691	-33.1	104296	108869	4.4	92752	83412	-10.1
	Other	140181	76525	-45.4	189438	195337	3.1	211927	184633	-12.9
	Total	**223406**	**132217**	**-40.8**	**293734**	**304205**	**3.6**	**304678**	**268045**	**-12.0**
SK-NSRB	Water Use	7541	6526	-13.5	8747	9136	4.4	7945	8825	11.1
	Other	7387	4965	-32.8	8956	9612	7.3	9825	9171	-6.7
	Total	**14928**	**11491**	**-23.0**	**17703**	**18748**	**5.9**	**17770**	**17996**	**1.3**
SK-SSRB	Water Use	14493	14395	-0.7	18737	19446	3.8	17228	17235	0.04
	Other	30483	19940	-34.6	32261	34545	7.1	35553	33003	-7.2
	Total	**44976**	**34335**	**-23.7**	**50998**	**53992**	**5.9**	**52781**	**50238**	**-4.8**
SK-SRB	Water Use	1939	2155	11.1	2955	2890	-2.2	2769	2707	-2.2
	Other	1580	1173	-25.7	2174	2329	7.1	2383	2209	-7.3
	Total	**3519**	**3328**	**-5.4**	**5129**	**5219**	**1.8**	**5152**	**4916**	**-4.6**
MB-SRB	Water Use	432	346	-19.8	418	442	5.8	395	343	-13.3
	Other	671	679	1.3	752	793	5.5	801	751	-6.2
	Total	**1103**	**1026**	**-7.0**	**1169**	**1234**	**5.6**	**1196**	**1094**	**-8.5**
SaskRB		**455802**	**269103**	**-41.0**	**584333**	**606190**	**3.7**	**605240**	**538855**	**-11.0**

2015 ISIO Model										
Hydro-economic Region	Sector	Observed 2009 Million CAD	Predicted 2009 Million CAD	Error (%)	Observed 2013 Million CAD	Predicted 2013 Million CAD	Error (%)	Observed 2014 Million CAD	Predicted 2014 Million CAD	Error (%)
AB-NSRB	Water Use	48651	48567	-0.2	76910	84704	10.1	80314	83250	3.7
	Other	119219	86078	-27.8	138690	161192	16.2	143533	161101	12.2
	Total	**167870**	**134645**	**-19.8**	**215600**	**245896**	**14.1**	**223847**	**244352**	**9.2**
AB-SSRB	Water Use	83225	70799	-14.9	104296	113412	8.7	109620	111690	1.9
	Other	140181	125550	-10.4	189438	221754	17.1	196194	221439	12.9
	Total	**223406**	**196349**	**-12.1**	**293734**	**335166**	**14.1**	**305814**	**333128**	**8.9**
SK-NSRB	Water Use	14493	14255	-1.6	18737	18758	0.1	18868	18315	-2.9
	Other	7387	6567	-11.1	8956	10168	13.5	9697	10181	5.0
	Total	**21880**	**20822**	**-4.8**	**27693**	**28926**	**4.5**	**28564**	**28496**	**-0.2**
SK-SSRB	Water Use	14493	14255	-1.6	18737	18758	0.1	18868	18315	-2.9
	Other	30483	25513	-16.3	32261	36777	14.0	34836	36841	5.8
	Total	**44976**	**39769**	**-11.6**	**50998**	**55534**	**8.9**	**53704**	**55155**	**2.7**
SK-SRB	Water Use	1939	2172	12.0	2955	2806	-5.0	2873	2864	-0.3
	Other	1580	1583	0.2	2174	2475	13.9	2355	2485	5.5
	Total	**3519**	**3755**	**6.7**	**5129**	**5281**	**3.0**	**5228**	**5349**	**2.3**
MB-SRB	Water Use	432	392	-9.2	418	479	14.6	411	450	9.5
	Other	671	701	4.6	752	823	9.5	785	820	4.5
	Total	**1103**	**1094**	**-0.8**	**1169**	**1301**	**11.3**	**1196**	**1270**	**6.2**
SaskRB		**455802**	**387878**	**-14.9**	**584333**	**661445**	**13.2**	**608242**	**657213**	**8.1**

Table 3-A-6. Predicted provincial output for different years based on the ISIO models for 2009 and 2013 and water intake in other years (in 2015 price levels)

2009 ISIO Model										
Province	Sector	Observed 2013 Million CAD	Predicted 2013 Million CAD	Error (%)	Observed 2014 Million CAD	Predicted 2014 Million CAD	Error (%)	Observed 2015 Million CAD	Predicted 2015 Million CAD	Error (%)
Alberta	Water Use	217571	227834	5	228741	226181	-1	193347	195052	1
	Other	357220	347080	-3	369769	342985	-7	398248	330123	-17
	Total	**574791**	**574914**	**0.02**	**598509**	**569165**	**-5**	**591595**	**525175**	**-11**
Saskatchewan	Water Use	60364	58617	-3	60326	56503	-6	55783	52947	-5
	Other	75836	80900	7	82140	79360	-3	83238	76482	-8
	Total	**136200**	**139517**	**2**	**142466**	**135863**	**-5**	**139021**	**129429**	**-7**
Manitoba	Water Use	31141	30935	-1	30454	29474	-3	28923	22940	-21
	Other	78954	84058	6	82287	82716	1	83917	78995	-6
	Total	**110095**	**114993**	**4**	**112742**	**112190**	**-0.5**	**112840**	**101935**	**-10**
2013 ISIO Model										
Province	Sector	Observed 2009 Million CAD	Predicted 2009 Million CAD	Error (%)	Observed 2014 Million CAD	Predicted 2014 Million CAD	Error (%)	Observed 2015 Million CAD	Predicted 2015 Million CAD	Error (%)
Alberta	Water Use	164576	104129	-37	228741	215984	-6	193347	164029	-15
	Other	284014	150735	-47	369769	356754	-4	398248	335130	-16
	Total	**448590**	**254864**	**-43**	**598509**	**572737**	**-4**	**591595**	**499159**	**-16**
Saskatchewan	Water Use	47881	43076	-10	60326	57171	-5	55783	53764	-4
	Other	67041	47358	-29	82140	75228	-8	83238	71364	-14
	Total	**114922**	**90435**	**-21**	**142466**	**132399**	**-7**	**139021**	**125128**	**-10**
Manitoba	Water Use	26091	23506	-10	30454	29194	-4	28923	22405	-23
	Other	72628	70372	-3	82287	77610	-6	83917	74153	-12
	Total	**98719**	**93879**	**-5**	**112742**	**106803**	**-5**	**112840**	**96558**	**-14**

Table 3-A-7. Predicted provincial output for different years based on the ISIO models for 2014 and 2015 and water intake in other years (in 2015 price levels)

2014 ISIO Model										
Province	Sector	Observed 2009	Predicted 2009	Error (%)	Observed 2013	Predicted 2013	Error (%)	Observed 2015	Predicted 2015	Error (%)
		Million CAD	Million CAD		Million CAD	Million CAD		Million CAD	Million CAD	
Alberta	Water Use	164576	112031	-32	217571	225925	4	193347	174406	-10
	Other	284014	137744	-52	357220	367915	3	398248	347645	-13
	Total	**448590**	**249776**	**-44**	**574791**	**593840**	**3**	**591595**	**522052**	**-12**
Saskatchewan	Water Use	47881	45290	-5	60364	62475	3	55783	56324	1
	Other	67041	44720	-33	75836	81670	8	83238	78040	-6
	Total	**114922**	**90010**	**-22**	**136200**	**144145**	**6**	**139021**	**134364**	**-3**
Manitoba	Water Use	26091	24759	-5	31141	31838	2	28923	23481	-19
	Other	72628	73476	1	78954	83076	5	83917	79012	-6
	Total	**98719**	**98235**	**-0.5**	**110095**	**114914**	**4**	**112840**	**102493**	**-9**
2015 ISIO Model										
Province	Sector	Observed 2009	Predicted 2009	Error (%)	Observed 2013	Predicted 2013	Error (%)	Observed 2014	Predicted 2014	Error (%)
		Million CAD	Million CAD		Million CAD	Million CAD		Million CAD	Million CAD	
Alberta	Water Use	164576	143186	-13	217571	234937	8	228741	232481	2
	Other	284014	230341	-19	357220	416806	17	369769	416393	13
	Total	**448590**	**373527**	**-17**	**574791**	**651742**	**13**	**598509**	**648875**	**8**
Saskatchewan	Water Use	47881	44217	-8	60364	59849	-1	60326	58081	-4
	Other	67041	57508	-14	75836	86035	13	82140	86023	5
	Total	**114922**	**101724**	**-11**	**136200**	**145884**	**7**	**142466**	**144104**	**1**
Manitoba	Water Use	26091	29615	14%	31141	35741	15%	30454	34488	13
	Other	72628	75619	4	78954	86013	9	82287	85794	4
	Total	**98719**	**105233**	**7**	**110095**	**121754**	**11**	**112742**	**120282**	**7**

Table 3-A-8. The number of models with larger errors in the predictions of the water-use sectors than the other sectors

	Total Predictions	Predictions with Larger Errors in Water Use Output
All Models	72	36
Dry Year Models	36	23
Wet Year Models	36	13

Chapter 4

Integrated Modelling to Assess the Impacts of Water Stress in a Transboundary River Basin: Bridging Local-scale Water Resource Operations to a River Basin Economy

Eamen, L., Brouwer, R., and Razavi, S. (2021). Integrated Modelling to Assess the Impacts of Water Stress in a Transboundary River Basin: Bridging Local-scale Water Resource Operations to a River Basin Economy. *Science of the Total Environment*, 149543. https://doi.org/10.1016/j.scitotenv.2021.149543

Abstract

In this chapter, we develop a hydro-economic modelling framework for river-basin scales by integrating a water resources system model and an economic model. This framework allows for the representation of both local-scale features, such as reservoirs, diversions, and water licenses and priorities, and regional- and provincial-scale features, such as cross-sectoral and inter-regional connectedness and trade flows. This framework is able to: (a) represent nonlinearities and interactions that cannot be represented by either of typical water resources or economic models; (b) analyze the sensitivity of macro-scale economy to different local water management decisions (called ‘decision levers’ herein); and (c) identify water allocation strategies that are economically sound across sectors and regions. This integrated model is applied to the multi-jurisdictional Saskatchewan River Basin in Western Canada. Our findings reveal that an economically optimal water allocation strategy can mitigate the economic losses of water stress up to 80% compared to the existing water allocation strategy. We draw lessons from our analysis and discuss the role of integrated inter-regional hydro-economic modelling in vulnerability assessments and informing sustainable decision making.

4.1. Introduction

Given the cascade of uncertainties associated with the projection of future climate and socioeconomic changes (New and Hulme, 2000; Haasnoot and Middelkoop, 2012; Daron, 2015), the traditional approach to water resources management that seeks solutions for ‘best-guess’ future scenarios increases the risk of water misallocation and erosion of system resilience (Rayner, 2000; Lempert et al., 2004; Maier et al., 2016). Under such circumstances, the decision-making approach needs to shift from relying on future predictions to understanding future vulnerabilities[2] (Lempert et al., 2004; Dessai et al., 2009; Herman et al., 2014; Maier et al., 2016; Bhave et al., 2016), a process known as Robust Decision Making (RDM) (Lempert et al., 2003; Lempert, 2019). The RDM approach seeks vulnerabilities by either identifying a range of values for uncertain variables that affect the performance of water management strategies and prevent them from meeting their objectives (Herman et al., 2014; Kwakkel and Jaxa-Rozen, 2016), or conducting a sensitivity analysis to evaluate the relative influence of uncertain variables or decision levers[3] on the performance of these strategies (Bryant and Lempert, 2010; Herman et al., 2015; Kwakkel and Haasnoot, 2019). By identifying these vulnerabilities, decision-makers can find sustainable and robust strategies that reduce system vulnerabilities and perform well across a wide range of plausible futures (Lempert and Groves, 2010; Herman et al., 2014; Bhave et al., 2016).

We apply this approach in a novel way to identify economic vulnerabilities in a river basin facing several water management challenges under climate change and socioeconomic development. The need for RDM becomes even more salient in transboundary river basins, where the trade-offs due to conflicting water uses under future water allocation strategies are expected to become more imminent. Vulnerabilities can in that case be identified by evaluating the economic impacts of changes in the water system. This includes the impacts on not only the sectors directly dependent on water and hence affected by changing water supply conditions, but also associated economic activities supporting the sector involved by respectively supplying it with the necessary input commodities or purchasing the sector’s output. Economic sectors hardly ever operate in isolation

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[2] Vulnerability is the tendency “to be adversely affected”, including “sensitivity” to and “lack of ability to adapt” to future conditions, e.g., climate change, policy interventions, socio-economic developments (IPCC, 2020).

[3] Decision levers are the actions that decision-makers consider in comprising their alternative strategies (Lempert et al., 2003).

from other sectors and depend on the supply of commodities and demand for their output from other sectors.

Hydro-economic models can capture this interconnectedness and identify the most influential decision levers on the river basin economy as a whole (Brouwer and Hofkes, 2008; Harou et al., 2009). By integrating relevant water and economic variables, a hydro-economic modelling framework allows the simultaneous evaluation of both the hydrological and economic impacts of external shocks such as climate change or water policy interventions. Hydro-economic models have been applied in a wide variety of water management studies dealing with water quantity and water quality problems (e.g., Duarte et al., 2002; Cai et al., 2003; Medellin-Azuara et al., 2007; Brouwer et al., 2008; Harou et al., 2010; Dellink et al., 2011; Razavi et al., 2013; Ward, 2014; Esteve et al., 2015; Levin-Koopman et al., 2017; Basheer et al., 2018; Mirchi et l., 2018; Souza da Silva and Alcoforado de Moraes, 2018; Kahsay et al., 2019; Dalcin and Marques, 2020; Do et al., 2020; Pérez-Blanco et al., 2020). However, not all hydro-economic models account for the broader economic impact implications of changes in water availability and water supply, as a result of climate change, socioeconomic development, or water policy interventions.

A traditional, but still popular, approach to hydro-economic modelling, particularly in the engineering community, is to connect a water resources system model to an economic partial equilibrium model, such as a production function. Such models are "partial" because their economic component only accounts for one part of the economy (e.g., agriculture) or one part of an economic sector (e.g., production/supply or consumption/demand) under fixed price ratios without considering its connections with the rest of the economy (e.g., Cai et al., 2003; Hurd and Coonrod, 2012; Razavi et al., 2013; Ward, 2014; Yang et al., 2014; Esteve et al., 2015; Escriva-Bou et al., 2017; Basheer et al., 2018; Mirchi et al., 2018; Do et al., 2020). Another commonly used approach, particularly in the economic community, is to develop a macro-economic model, e.g., a computable general equilibrium or an input-output model, that includes a set of water supply and use data (e.g., Duarte et al., 2002; Brouwer et al., 2008; Calzadilla et al., 2010; Zhang and Anadon, 2014; Levin-Koopman et al., 2017; Ridoutt et al., 2018; Almazán-Gómez et al., 2019; Cazcarro et al., 2020; Teotónio et al., 2020). This modelling approach considers the economic interconnectedness among different sectors and/or regions. However, it usually does not capture the interactions among different elements of the water resources system. Only a limited number of studies used, to the best of the authors' knowledge, a fully integrated modelling approach that brings together models of water systems and economic systems (e.g., Jonkman et al., 2008; Dellink et al., 2011; Kahsay et al., 2019; Tanoue et al., 2020).

This gap in the literature motivates the present study to develop an integrated hydro-economic model for a transboundary river basin by coupling a detailed water resources system model and a macro-economic model to help decision-makers identify the spatial and sectoral distribution of economic impacts and support them in developing sustainable and robust strategies. In doing so, we couple a water resources system model (developed in MODSIM-DSS) (Shah et al., Under review) to an inter-regional supply-side input-output (ISIO) model that includes water intake for sectors that rely directly on freshwater for their production (Chapter 2). Unlike studies that apply either of these two models separately as stand-alone models, this integrated modular model captures the hydrological connectedness of sub-basins (regions) as well as the economic connectedness of the activities in these regions, and consequently the direct and indirect economic impacts of changes in water availability. The water resources model is capable of simulating the water resources system under different water availability scenarios and estimate changes in the water supply to different water-use sectors accounting for demand priorities, reservoir operational rules, and non-linearities in the water resources system, which is then fed into the macro-economic input-output model.

Although we do not test the robustness of alternative water allocation strategies across a wide range of future scenarios here, our findings help identify strategies that can mitigate the economic impacts of future droughts. This helps to reduce the number of alternative water allocation strategies to be tested for their robustness in a robust decision-making framework and consequently reduce the computational burden of this process.

As a case study, we focus on a large multi-jurisdictional river basin in Western Canada, the Saskatchewan River Basin (SaskRB), which experiences various water management challenges including water allocation among competing use(r)s (e.g., Wheater and Gober, 2013). These challenges are expected to become even more pronounced under future climate change and increasing water scarcity conditions. Existing studies that attempt to assess the impacts of future climate conditions and possible water allocation policies on different parts of the SaskRB (e.g., Wang et al., 2008; Cutlac and Horbulyk, 2011; He et al., 2012; Ali and Klein, 2014; Hassanzadeh et al., 2016) focus on a specific part of the SaskRB and not the entire basin across the provinces Alberta, Saskatchewan, and Manitoba. These studies furthermore ignore relevant cross-sectoral and inter-regional connections and hence the possible indirect impacts of future hydrological changes on the river basin economy.

To manage the SaskRB's water resources sustainably and robustly under increasing demand for freshwater by competing water users, decision-makers need to understand which sectors and regions are likely most affected and how this influences the river basin's economy as a whole. The answer to these questions is then used to design an alternative water allocation strategy to cope with possible future droughts. This alternative is based on economic considerations under future water supply restrictions by searching for a water allocation strategy that minimizes the impact of water stress on the entire economy of the SaskRB. Finally, we apply the integrated hydro-economic model to stress-test this water allocation strategy and compare its economic performance with the existing water allocation system in the SaskRB.

The rest of this chapter is organized as follows. Section 4.2 describes the methodology for developing the integrated hydro-economic model. Section 4.3 outlines the procedure of assessing the economic vulnerabilities, including identifying the most influential decision levers and stress testing water allocation alternatives using the integrated hydro-economic model. Results are presented in Section 4.4 followed by discussion and conclusions in Section 4.5.

4.2. Integrated Hydro-Economic Modelling Framework

4.2.1. General Methodology

In this study, the water resources system model of the integrated hydro-economic model is developed using a generic modelling program, namely MODSIM-DSS. MODSIM is a modelling program for river basin simulation developed at Colorado State University (Shafer and Labadie, 1978). The model consists of a network of nodes and links, where nodes represent water resource and demand sites and links are carriers such as rivers, canals, or pipelines that connect these nodes. Demand nodes are represented in the model by defining properties such as water demand time series, water allocation priority, etc. Reservoirs are also defined in this model as nodes with associated properties, including storage capacity, rule curve, hydraulic properties, net evaporation time series, etc. The model simulates interactions between available water resources and demands under different climate and policy conditions and provides the economic model with the amount of water supplied to various economic sectors. MODSIM is applied in water resources system modelling as a stand-alone model as well as in combination with other models, including economic, water quality, and groundwater models (e.g., Dai and Labadie, 2001; Morway et al., 2016; Shourian and Mousavi, 2017; Emami and Koch, 2018; Fereidoon and Koch, 2018). The water resources system model developed in this study in MODSIM is presented in more detail in Section 4.2.2.

The economic component of our integrated hydro-economic model is an inter-regional supply-side input-output (ISIO) model. This model evaluates the direct and indirect economic impacts of exogenous changes based on an equation that links value added created by different input factors to sectoral output (Ghosh, 1958). This equation uses existing supply and use tables built from economic transaction data in a particular year in the past by statistical offices. In a commodity-by-industry (or rectangular) input-output system where each sector can produce more than one commodity, this equation is described in matrix notation as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{B}^{\mathrm{T}})^{-1}\tilde{\mathbf{v}} \tag{4.7}$$

where $\mathbf{x}$ is a vector of gross sectoral output, $\mathbf{I}$ is an identity matrix, and $\tilde{\mathbf{v}}$ is the vector of the sectoral value added[4]. In an economy with n sectors, $\mathbf{B}$ is a nxn matrix consisting of elements b_{ij} that represent the purchases by sector j from sector i per monetary unit of output of sector i. $\mathbf{B}$ is known as the allocation coefficient matrix, and $(\mathbf{I} - \mathbf{B}^{\mathrm{T}})^{-1} = \mathbf{G}$ is the output inverse. To calculate $\mathbf{B}^{\mathrm{T}}$ in a rectangular IO system, the use matrix is divided by the total outputs of commodities, resulting in matrix $\mathbf{H}$, and the supply matrix is divided by the total output of industries, resulting in matrix $\mathbf{C}$. Then, $\mathbf{B}^{\mathrm{T}}$can be presented as $\mathbf{B}^{\mathrm{T}} = \mathbf{H}^{\mathrm{T}}\mathbf{C}$.

To apply this model in a water resources management context, IO data typically published for administrative geographical units (a state or province) need to be made compatible with water use data collected within the hydrological boundaries of a river basin. To this end, provincial IO tables are disaggregated to sub-basin scale using labor force data for different sectors and population data

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[4] In this chapter bold uppercase letters represent matrices and bold lowercase letters vectors, while $^{-1}$ refers to the matrix inversion operator, and $^{\mathrm{T}}$ the matrix transpose operator.

for final demand available at lower census sub-division scale. Then, inter-sub-basin IO tables are estimated using intra- and inter-provincial trade flow data. Finally, the IO tables created at sub-basin and inter-sub-basin levels are re-assembled to create the ISIO model for the entire river basin (the methodology is described in detail in Chapter 2).

To include water in the ISIO model, sectoral water productivity is used as the monetary output of each sector per physical water supply unit. Then, the value of change in the amount of water supply is given by $\Delta\mathbf{v}_{\mathrm{w}} = \mathbf{p}\Delta\mathbf{w}$, where $\Delta\mathbf{v}_{\mathrm{w}}$ is the value of change (\$), $\mathbf{p}$ is water productivity (\$/m^3), and $\Delta\mathbf{w}$ is the change in the amount of sectoral water supply (m^3) coming from the water resources system model. Considering this value of change as a part of sectoral value added, we have:

$$\Delta\mathbf{x} = \mathbf{G}\Delta\mathbf{v}_{\mathrm{w}} \tag{4.8}$$

where $\Delta\mathbf{x}$ reflects changes in sectoral gross output and $\mathbf{G}$ is the above mentioned output inverse. For more detailed information about the ISIO model, see Chapter 2.

In this study, we define water supply as the amount of water that is withdrawn by or transferred to a sector, a part of which is consumed for production (i.e., water use), and the rest returns to the water system as return flow. Here, we assume that the amount of water used by different sectors changes proportionally to any changes in water supply. In other words, we consider the ratio of the return flow to the water supply to be constant so that any changes in the amount of water supplied to a sector affect the water use of that sector by the same proportion. This assumption is rooted in analyzing this ratio based on water consumption data for the Saskatchewan River Basin over time (AEP, 2018). Furthermore, the water productivity value that is calculated in this study is the productivity of the raw water supply. This means that the productivity of sectors that receive water from the "Utilities" sector is not considered in this calculation. The monetary transactions between these latter sectors and the "Utilities" sector are already included in the IO tables.

4.2.2. Developing an Integrated Hydro-Economic Model for the Saskatchewan River Basin

The integrated model described above is developed for the Saskatchewan River Basin (SaskRB) in Western Canada. Similar to the previous chapters, the integrated hydro-economic model developed in this study considers parts of each main sub-basin, i.e., the North Saskatchewan River Basin (NSRB), South Saskatchewan River Basin (SSRB), and Saskatchewan River Basin (SRB), within the three provinces as the hydro-economic regions in the model. It is assumed here that the main water resources for the water-use sectors and rain-fed agriculture are the Saskatchewan River and precipitation, respectively. Hence, the limited use of other water sources, such as groundwater, recycled water, etc., is not considered in this model due to the lack of reliable data.

The water resources system model of the SaskRB consists of eight sub-models, namely the North Saskatchewan in Alberta and Saskatchewan, the South Saskatchewan in Alberta and Saskatchewan, the Saskatchewan River in Manitoba, TransAlta, Highwood, and the Southern Tributaries. The latter three sub-models are parts of the South Saskatchewan River system in Alberta that were modeled separately. The model includes irrigation, non-irrigation, and hydropower demand nodes. Overall, the SaskRB water resources system model includes 174 irrigation demand nodes, 232 non-irrigation demand nodes, 58 storage reservoirs, and 30 hydropower plants. The water resources system model of the SaskRB works on a weekly basis (Shah et al., Under review). The schematic of the integrated hydro-economic model of the SaskRB is presented in Figure 4.1. The hydro-economic regions in the model are the North Saskatchewan (AB-NSRB) and South Saskatchewan (AB-SSRB) sub-basins in Alberta; the North Saskatchewan (SK-NSRB), South Saskatchewan (SK-SSRB), and Saskatchewan River (SK-SRB) sub-basins in Saskatchewan; and the Saskatchewan River Sub-basin (MB-SRB) in Manitoba.

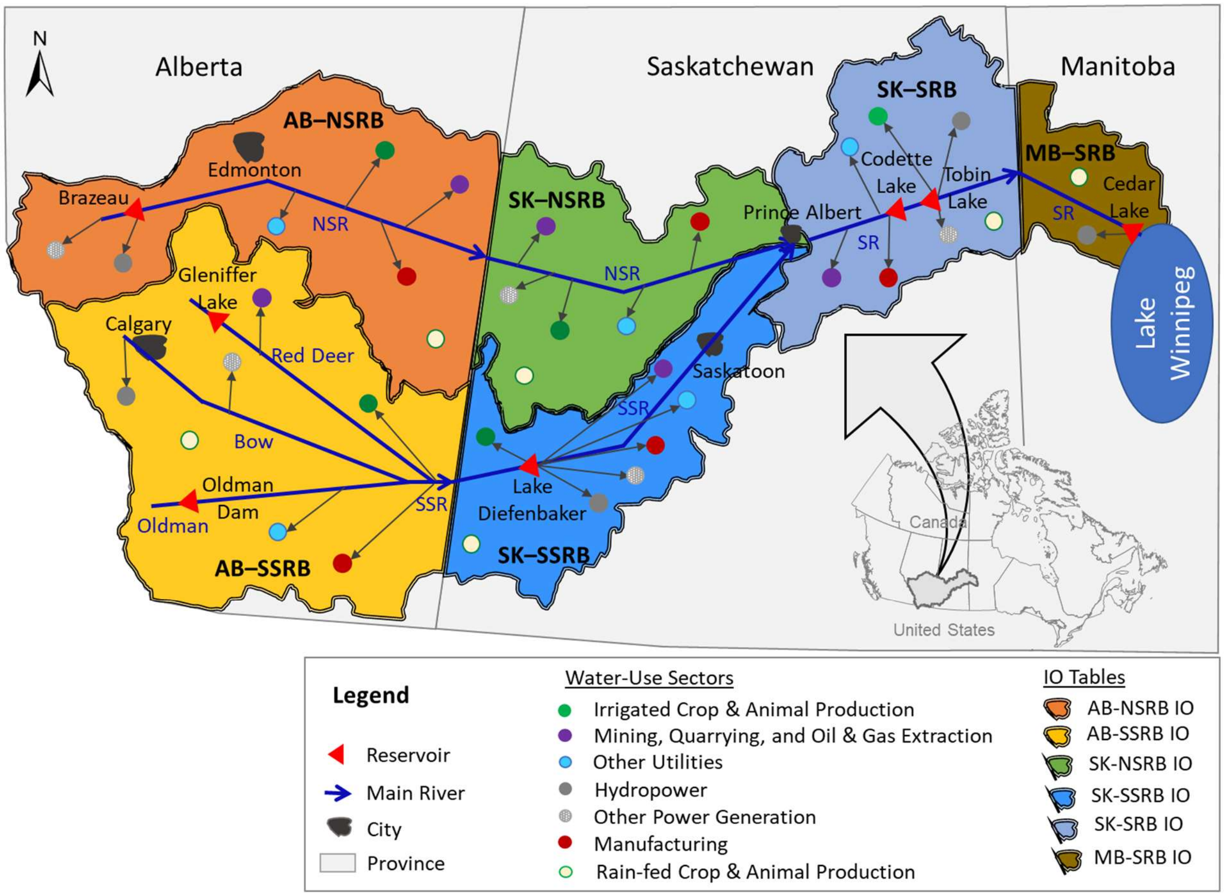


Figure 4.1. The schematic of the integrated hydro-economic model for the Saskatchewan River Basin. This figure is prepared for illustrative purposes and does not include all details of the SaskRB water resources system model. For example, the total number of reservoirs in this river basin is 58, while only some are shown in this schematic.

The ISIO model of the SaskRB was developed at the level of hydro-economic regions and on an annual basis using the summary level of the input-output data for the year 2015, which includes 35 sectors based on the Canadian System of National Accounts. This year was selected as it was the most recent year for which the IO data were available. We also used the model developed for 2014 in Chapter 2 for the analysis in this chapter. However, as no changes were detected in the pattern of results generated for the years 2014 and 2015, only results for the year 2015 were presented here. The integrated hydro-economic model is considered here to work on an annual basis with the finest spatial scale set to hydro-economic regions. As such, the weekly water supplies simulated by the water resources system model are aggregated to the annual level before entering the ISIO model. To tackle the spatial incompatibility between the two models, the demand nodes of the water resources system model in each hydro-economic region were aggregated to form demand groups. For example, the integrated model includes one irrigation demand group in each region instead of several irrigation nodes (Figure 4.1).

To make industry classifications in the two models compatible, the "Crop and animal production" sector in the IO tables was disaggregated into irrigated and rain-fed agriculture using the ratio of irrigated production to the total agricultural production (Chapter 2). The "Utilities" sector from the IO tables was disaggregated to "Hydropower generation", "other electric power generation", and "Other utilities" using information from the IO tables' detailed level (Statistics Canada, 2018a) and the share of hydropower in power generation in each province (CER, 2020). Finally, the non-irrigation demands in the water resources system model were separated into "Mining, quarrying, and oil and gas extraction", "other electric power generation", "Other utilities", and "Manufacturing" (Figure 4.1) using the water licensing information in the SaskRB (AEP, 2018). These integration challenges will be expanded in Chapter 5.

Allocating water among competing demands has been challenging in the SaskRB (Halliday and Associates, 2009; Government of Alberta, 2010; Wheater and Gober, 2013). Upstream Alberta has stopped issuing licenses in some sub-basins of the SSRB (i.e., "closed" sub-basins) due to water over-allocation issues (Wheater and Gober, 2013; Government of Alberta, 2010), while downstream Saskatchewan is planning for new developments (SWSA, 2012) that demand more water from the river. According to the Master Agreement on Apportionment in 1969, the two upstream provinces sharing this river basin are committed to transferring one-half of their annual natural flow to their downstream provinces. Additionally, in the SSRB, Alberta is required to transfer a minimum flow to the downstream Saskatchewan all the time (Prairie Provinces Water Board, 1969).

The existing water allocation system in the SaskRB is a licensing system based on priorities. Water was traditionally allocated based on a "first-in-time, first-in-right" licensing system in the three provinces sharing the SaskRB (Brooymans, 2011). Alberta and Manitoba continue to use that system. However, the Saskatchewan Water Security Agency has adopted a new system since the 1980s (SWSA, 2012), and the licenses are issued now based on the province's terms and conditions, which are not always based on economic considerations, and are for a specific duration instead of in perpetuity (Government of Saskatchewan, 2018). Water allocation priorities, according to these water allocation systems are assigned to the corresponding demand nodes in MODSIM. To ensure that water is allocated to different demand nodes based on these priorities, a penalty value is considered for each node following the node's priority, meaning that the higher the priority of a node, the higher the penalty value would be in case of water shortage in that node. Then, for each simulation, MODSIM allocates water among demand nodes in a way that the total penalty at each time step is minimized, similar to the Water Evaluation and Planning (WEAP) model (Sieber and Purkey, 2015), the California Water Resources Simulation Model (CALSIM) (Draper et al., 2003) or the Water Resources Management Model (WRMM) of Alberta Environment and Parks (2002). The next section outlines how the hydro-economic model is able to support water allocation decisions, particularly under drought conditions.

4.3. Assessing Economic Vulnerabilities

Figure 4.2 depicts how the hydro-economic model helps to evaluate the economic impacts of different scenarios about climate change, socioeconomic development, and/or policy intervention. First, the possible impacts of these scenarios on water supply and demands are estimated by the water resources system model (MODSIM), which simulates water supply to various economic sectors. Sectoral water supply is then entered into the economic ISIO model, which estimates the impact on sectoral output and Gross Domestic Product (GDP) at the scales of the hydro-economic regions, the provinces, and the entire river basin.

In order to assess economic vulnerabilities, the most influential decision levers are identified by assessing the sensitivity of the economy of the SaskRB to changes in sectoral and regional water supply. Then, a stress test is conducted to investigate the response of the SaskRB's hydro-economic system under alternative water allocation strategies, comprising these decision levers, to different levels of water stress. These steps will be described in more detail in the next sections.

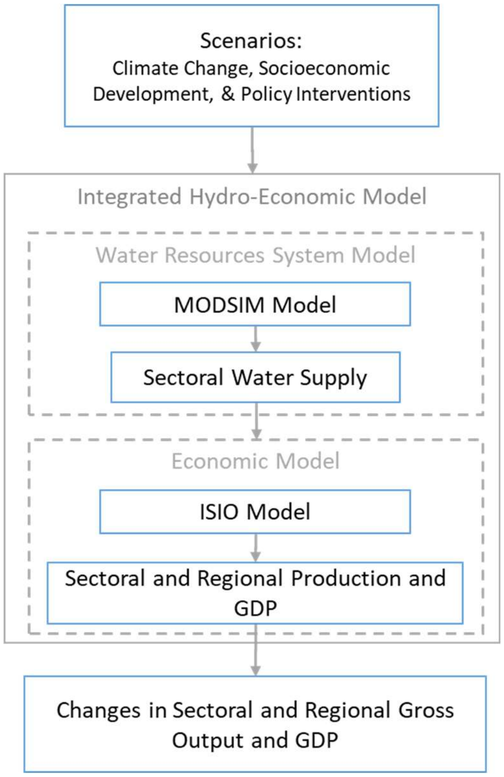


Figure 4.2. The structure of the integrated hydro-economic model of the Saskatchewan River Basin

4.3.1. Identifying the Most Influential Decision Levers on the River Basin Economy

Changes in gross output are estimated to find the economic loss due to different decision levers. Since the focus of this study is on water allocation, each decision lever is considered to change the water supply to either a sector or a region in the multi-sectoral and multi-regional river basin. This configuration of decision levers facilitates analyzing the effect of each decision lever on the economy of the river basin and, consequently, assessing the relative influence of different decision levers. In a river basin with n sectors and l different regions, $n + l$ decision levers can be identified, where one region includes all sectors and hence no combinations between individual sectors and individual regions are created here (the number of combinations would in that case be $n \times l$). In order to assess the economic impact of each decision lever, water supply to each sector or region is changed percentagewise. Let $\mathrm{w}_{\mathrm{i}}^{\mathrm{r}}$ to be the amount of water supply to sector i in region r under the existing water allocation system and β be the percent change in corresponding water supply. Then, the change in water supply to sector i in region r due to decision lever $m \in [1, n + l]$ is defined as:

$$\Delta \mathrm{w}_{\mathrm{i}}^{\mathrm{r}}(m) = \begin{cases} \beta \mathrm{w}_{\mathrm{i}}^{\mathrm{r}} & \mathit{if}\ m = i\ \ \mathit{or}\ m = r \\ 0 & \mathit{otherwise} \end{cases} \tag{4.9}$$

Having a vector $\Delta\mathbf{w}(\mathrm{m})$ for each decision lever that consists of $\Delta \mathrm{w}_{\mathrm{i}}^{\mathrm{r}}(m)$ elements for the entire river basin, we can estimate the value of changes in the water supply $\Delta\mathbf{v}_{\mathrm{w}}(\mathrm{m})$ and the associated changes in gross output $\Delta\mathbf{x}\,(\mathrm{m})$ due to that decision lever through Eq. (4.2). A sensitivity coefficient is defined as the percentage change in gross output due to a percentage change in water supply due to each decision lever. The sensitivity coefficient, SC, for the decision lever m can be calculated as follows:

$$\mathrm{SC}(\mathrm{m}) = \frac{{}^{\Delta\mathbf{x}}\!/_{\mathbf{x}_0}\,(\mathrm{m})}{{}^{\Delta\mathbf{w}}\!/_{\mathbf{w}_0}\,(\mathrm{m})} \tag{4.10}$$

where the subscript 0 refers to gross output and water supply under the baseline or status quo scenario. This coefficient is used to identify the most influential decision levers on the economy of the river basin. To further rank the decision levers and identify which sectors and regions are most costly to reduce water from, their estimated economic loss was also related to a physical unit - i.e., cubic meter (m^3) per year - of reduction in water supply by dividing GDP losses in each sector and region by the volume of water equivalent to the considered percentage reduction in water supply.

Two groups of decision levers were selected in this study, i.e., changing water supply among the main water-use sectors and the hydro-economic regions of the SaskRB (Table 4.1). The first group of levers addresses the conditions under which water authorities might decide to transfer a part of one sector's water entitlement to another sector to offset a part or all of the reduction in the latter sector's water supply. We defined these sectoral levers here as decision levers that reduce 1% of water supplied to each sector in the SaskRB. For example, the decision lever "Irrigated" represents the conditions under which water supply to the "Irrigated crop and animal production" sector is reduced by 1%. Note that the purpose of this decision lever is to assess the sensitivity of the economy to a 1% reduction in water supply to different water-use sectors, not the economic impacts of different water reallocation scenarios. Therefore, we only reduced the amount of water from a certain sector under each decision lever by 1% and evaluated its impact on the economy as a whole without adding this water to the other sectors. It is assumed that under these levers, the water supply to each sector is the whole amount of water supplied to that sector in the SaskRB. It should be noted that the relatively small marginal change in the water supply here (i.e., 1%) is considered due to the linear structure of the ISIO models. Since the economic system might react in a non-linear way to high perturbations in the water supply, this relatively small change is considered here for the sensitivity analysis to avoid disproportionate and non-linear economic responses.

Table 4.1. The decision levers of the SaskRB for water allocation under water stress

Sectoral Decision Lever	**Reducing 1% from water supply to main water-use sectors**	**Regional Decision Lever**	**Reducing 1% from water supply to hydro-economic regions**
Irrigated	Irrigated- crop and animal production	AB-NSRB	North Saskatchewan in Alberta
Mining	Mining, quarrying, and oil and gas extraction	AB-SSRB	South Saskatchewan in Alberta
Other Utilities	Utilities other than electricity	SK-NSRB	North Saskatchewan in Saskatchewan
Other Power Generation	Other electric power generation	SK-SSRB	South Saskatchewan in Saskatchewan
Manufacturing	Manufacturing	SK-SRB	Saskatchewan in Saskatchewan
Rain-fed	Rain-fed- crop and animal production		

The main water-use sectors were studied individually, and the rest of the economy was aggregated into the "Other" sector. Since Hydropower demand is a non-consumptive demand, meaning that the amount of water diverted for hydropower generation returns to the river system downstream of the power plant, we did not consider hydropower as one of the sectoral decision levers in this study. The water resources system model does not include rainfed crop farming, the dominant form of agriculture in the SaskRB. Only about 6% of the cultivated land in Alberta and less than 1% in Saskatchewan and Manitoba are under irrigation (Statistics Canada 2018b and 2018c). Therefore, water supply reductions consist in this case of reduced precipitation for "Rain-fed crop and animal production" as one of the decision levers. Although the amount of precipitation cannot be controlled by water authorities, this analysis helps us to understand the influence of rainfed agriculture on the economy of the whole SaskRB.

The second group of decision levers refers to situations under which water managers agree on using part of the water allocated to one region to mitigate the economic impacts of water shortage in another region. These levers are also considered to reduce 1% of water supplied to a region in the SaskRB. For these levers, water allocated to one region includes the total amount of water supplied to all water-use sectors in that region. For instance, under the AB-NSRB decision lever, a part of the water entitled to all the water-use sectors in this region is reduced to be used in other regions. The relative influence of this decision lever on the economy of the SaskRB is hence evaluated by assuming that 1% of the water supply in AB-NSRB is reduced. The integrated hydro-economic model is then used to estimate the corresponding reduction in gross output and GDP and provides input for the calculation of the sensitivity coefficient (SC) using Eq. (4.4) to identify the most influential decision levers. It should be noted that since we excluded hydropower from our sectoral decision levers, and this sector is the only main water-use sector (other than rain-fed agriculture) in MB-SRB, we did not include this region in our regional decision levers.

A uniform water reduction from each sector in the entire SaskRB is considered here, assuming that comprehensive decisions could be made at the large-scale level for the whole river basin in the time of drought. However, different jurisdictions might take different approaches in managing their water demands in each of the three provinces sharing the SaskRB.

4.3.2. A Stress Test of Water Allocation Alternatives

In this section, we evaluate the impact of alternative water allocation scenarios on the SaskRB as a whole. This is referred to here as 'stress testing'. To stress test the water system, first a set of scenarios are generated that represent plausible changes in water availability due to possible climate change, socioeconomic developments, and/or policy interventions. Then, the economic impacts of these scenarios on the river basin are evaluated using the integrated hydro-economic model. To evaluate the impacts of changes in water availability, let $\mathrm{w_i^r}(0)$ to be the amount of water supply to sector i in region r under the water availability baseline scenario. Simulating each water availability scenario k by the water resources system model, we estimate the percentage change in water supply to sector i in region r under that scenario, i.e., $\mathrm{\alpha_i^r}(\mathrm{k})$. Hence, the change in the amount of water supply to sector i in region r would be $\Delta \mathrm{w_i^r}(\mathrm{k}) = \mathrm{\alpha_i^r}(\mathrm{k}) \times \mathrm{w_i^r}(0)$. For each water availability scenario k, $\Delta\mathbf{w}(\mathrm{k})$ is a vector of $\Delta \mathrm{w_i^r}(\mathrm{k})$ elements showing the changes in water supply to different sectors in regions of the river basin under that scenario. The value of these changes under each scenario can be calculated using the water productivity $(\mathbf{p})$ as:

$$\Delta \mathbf{v}_{\mathrm{w}}(\mathrm{k}) = \mathbf{p}\Delta \mathbf{w}(\mathrm{k}) \tag{4.5}$$

The consequent change in sectoral gross output due to each scenario k can be estimated using Eq. (4.2), as follows:

$$\Delta \mathbf{x}\ (\mathrm{k}) = \mathbf{G}\Delta \mathbf{v}_{\mathrm{w}}(\mathrm{k}) \tag{4.6}$$

As we are interested in water allocation under future water scarcity conditions, a range of reductions in water availability in the SaskRB was considered accounting for plausible changes in future climatic and socioeconomic conditions. Notably, according to the long-term (100 years) annual streamflow data of the Saskatchewan River System, during the past dry years, e.g., in 2001, the annual flow of the South Saskatchewan River in Alberta reached 56% and 71% lower than the flow in 2015 (i.e., the reference year) and the long-term average flow, respectively. Hence, we selected first a range from 0% to 90% reduction in the water availability in the SaskRB on an annual basis to account for plausible drivers of the reduction, assuming that the temporal pattern of water availability remains unchanged. Nine 'stress-test scenarios' were created. The baseline scenario is a zero percent reduction in water availability, while scenarios 1 to 9 reduced 10% to 90% of the available water. These scenarios were simulated using the integrated hydro-economic model, as shown in Figure 4.2. For example, under the first scenario, 10% was reduced from the inflow that enters the SaskRB, including water coming from headwaters of both the North Saskatchewan and South Saskatchewan Rivers. The water resources system model simulates the interactions between water supply and demand nodes and estimates the amount of water that would be supplied to each sector under this 10% water availability reduction scenario. These sectoral water supplies are then fed into the ISIO model, and their sectoral output is estimated, accounting for sectoral and spatial spillover effects across hydro-economic regions. This procedure was repeated for the other stress test scenarios, while the same range of water reduction scenarios was considered for summer precipitation for rainfed agriculture.

This is an explorative exercise to provide us with insight into the distribution of economic impacts and relative importance of different sectors/regions in the face of increasing pressure on water resources in the SaskRB. Using the ISIO model, as the economic component of the model, we investigate the instantaneous effects of these levels of stress on the existing economy (i.e., the economy in 2015) by testing how the economic structure would absorb these shocks by reducing economic output (which is referred to as static comparative analysis in economics).

The nine stress test scenarios, reducing water supply between 10% and 90%, were evaluated under two specific water allocation alternatives, namely the existing water allocation system in the river basin and a water allocation based on an economic optimization procedure. Hence, in this stress test, we examined two different economic responses to the reduction in water availability. The first response is, like in the previous section, based on the current water allocation system described in Section 4.2.2. The other economic response is briefly outlined below.

The economically optimal allocation of water is based on the principle that under increasing future water shortages or restrictions, water is allocated to sectors in such a way that their gross output (or river basin GDP) experiences the least deviation from the baseline gross output (or river basin GDP). In other words, water reductions are absorbed in the river basin economy at the least cost possible. The objective function and constraints underlying this economic optimization procedure (in the ISIO model) can be written as follows:

$$\text{Min } \Delta\mathbf{x} = \mathbf{x_0} - \mathbf{x_{scen}} \tag{4.7}$$

$$\text{s.t. } \boldsymbol{\gamma}\mathbf{x_0} \leq \mathbf{x_{scen}} \leq \mathbf{x_0} \tag{4.8}$$

$$\sum \mathrm{w}_i = \mathrm{w}_{\mathrm{scen}} \tag{4.9}$$

where $\mathbf{x_0}$ is the baseline gross output, $\mathbf{x_{scen}}$ is gross output under the water restricted scenario, $\boldsymbol{\gamma}$ is a vector of $\gamma_i \in [0,1]$ elements that show the minimum level of output required to be produced by each sector, $\mathrm{w}_i \in [0, \mathrm{w}_{\mathrm{Scen}}]$ is water supply to sector i, and $\mathrm{w}_{\mathrm{scen}}$ is the total available water under the water restricted scenario. The first constraint (Eq. 4.8) ensures that gross output under the water restriction scenario never exceeds the baseline output and meets the minimum level required for inter-industry transactions. The second constraint (Eq. 4.9) keeps the total amount of allocated water equal to the total available water under the water restricted scenario. Note that physical possibility of transferring water from one sector/region to another is not investigated here.

4.3.3. Modelling Assumptions and Limitations

As mentioned earlier, the structure of the ISIO model is linear. In our sensitivity analysis, we consider a relatively small change in water supply (i.e., 1%), and therefore this linearity is not expected to change or affect the results in a major way. In the stress test, however, the assumption that the economy of the river basin also responds linearly to higher levels of perturbations in water availability is perhaps more questionable and may have implications for the results. We are unfortunately unable to assess the extent to which this assumption affects the results. Because the assumption is constant across all perturbations and the purpose of the stress test is to evaluate the relative distribution of the economic impacts across regions and sectors rather than their absolute magnitude, the potential role of such errors is expected to have limited influence on the relative magnitude of the impacts.

In our stress test, we assume that the quantity of available water needed for economic production (e.g., during the cropping season) would be reduced to different levels as a result of the impact of drivers such as climate change and socioeconomic developments within the river basin (e.g., expansion of irrigated land). This somewhat rudimentary scenario analysis was applied to explore how increasing pressure on the SaskRB's water resources would affect different economic sectors and regions in the river basin and their relative importance in the distribution of the direct and indirect economic impacts. We did not create new or downscale existing, more formal climate and land-use change scenarios here. By imposing increasing water availability restrictions, we investigate the instantaneous effects of different levels of water stress on the existing river basin economy (i.e., the economy as we knew it in the year 2015) by testing how the existing economic structure would absorb these shocks by reducing economic output in a comparative static economic analysis (Ritschard, 1983).

Whereas climate change affects both the availability of water and water demand, the inclusion of socioeconomic developments in the river basins affects demand for water. We, however, did not account for formal scenarios for changes in demands under climate change and future developments, which should also be kept in mind while interpreting the results of the study.

Finally, there are no additional costs considered here in reallocating resources to generate gross output under the imposed water supply restrictions; for example, labor is assumed to be completely mobile between different economic sectors. This is typically referred to as transaction costs in economics (Williamson, 1994).

4.4. Results

4.4.1. The Most Influential Decision Levers in the Saskatchewan River Basin

Figure 4.3 presents the responses of economic sectors in the SaskRB to the sectoral and regional decision levers that could be considered in the future under increasing water shortage conditions. The colored lines refer to the different decision levers (sectoral ones on the left hand side and regional ones on the right hand side). Sectors are most sensitive to reductions in their own water supply, and changes in the water supply to “Manufacturing” and “Mining, quarrying, and oil and gas extraction” have the biggest impacts on the gross output of the other sectors. As can be seen in Figure 4.3(a), reducing water supply to the “Manufacturing” sector is the most influential decision lever on other sectors, except for “Other power generation” and “Other utilities”, which are more affected by “Mining, quarrying, and oil and gas extraction”. The least influential sectoral decision lever is “Other utilities”.

From Figure 4.3(b), we can see that restricting the water supply in AB-SSRB has the highest impact on gross output of all sectors, closely followed by AB-NSRB. The next relatively important regional decision lever is reducing water supply in SK-SSRB. All sectors are least sensitive to water supply restrictions in SK-SRB.

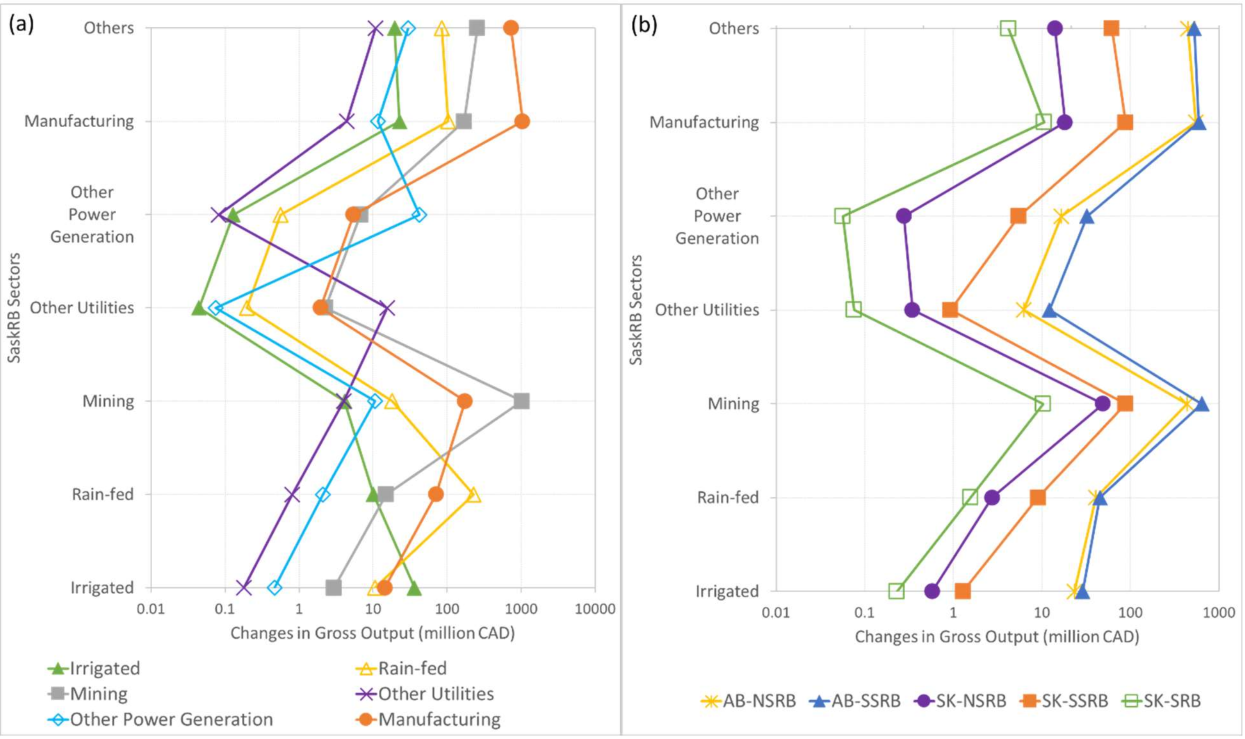


Figure 4.3. Reductions in the gross output of economic sectors in the Saskatchewan River Basin due to (a) sectoral and (b) regional decision levers in the year 2015. The impact on sectoral gross output is shown on a logarithmic (horizontal) scale, and the sectors affected by the lever are shown on the vertical scale.

Figure 4.4(a) presents the spatial distribution of the calculated sensitivity coefficients related to the sectoral decision levers, and Figure 4.4(b) the same sensitivity coefficients related to the regional decision levers. Starting with Figure 4.4(a), gross output in all regions except SK-NSRB and MB-SRB is most sensitive to reducing water supply to the "Manufacturing" sector. For example, in AB-SSRB, we observe the highest sensitivity coefficient (0.327%) is related to a water reduction in "Manufacturing". Gross output in SK-NSRB and MB-SRB are most sensitive to reductions in the water supply to "Mining, quarrying, and oil and gas extraction" and "Rain-fed crop and animal production", respectively. Furthermore, gross output is least sensitive to water supply restrictions in "Other utilities" in all regions of the SaskRB.

Figure 4.4(b) shows that gross output in each region is most sensitive to changes in its own water supply. The results in this figure also reveal that reducing water supply in AB-SSRB and AB-NSRB are the most influential regional levers. These two decision levers even have a bigger impact on regional gross output in Saskatchewan than the Saskatchewan regions have on each other's output. For instance, gross output in SK-SRB is more sensitive to reductions in the water supply in AB-SSRB than SK-SSRB. The sensitivity coefficient in SK-SRB is 0.055% when reducing water supply by 1% in the former and 0.026% when reducing water supply in the latter.

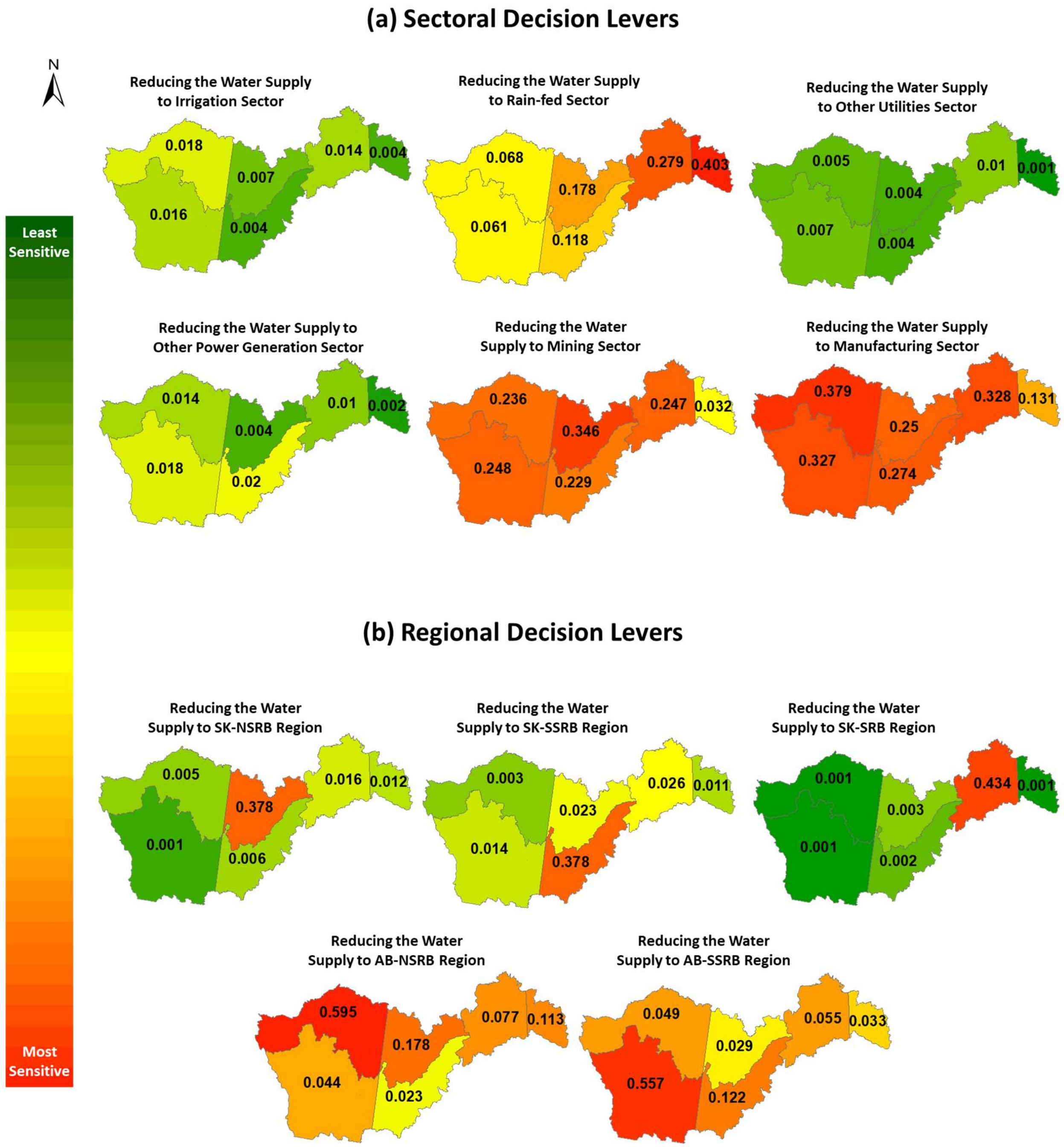


Figure 4.4. Spatial distribution of the sensitivity coefficients related to (a) sectoral and (b) regional decision levers

The relative ranking of the levers due to a 1% reduction in their water supply is presented in the Appendix to this chapter. To identify the most costly sectors/regions to reduce water from (if a certain amount of water is available to be allocated among them), the levers are ranked based on the economic loss associated with reducing one m^3 from their annual water supply. Figure 4.5 shows the ranking of total economic losses in the SaskRB related to sectoral and regional decision levers per a cubic meter of water reduction in a year, where economic loss is again measured on a logarithmic scale. Higher-ranked levers have higher economic losses due to a unit of water reduction. Based on this absolute instead of relative water reduction measure, the ranking of levers changes slightly. Reducing 1 m^3/year of water supply is most costly in “Mining, quarrying, and oil and gas extraction”, followed by “Manufacturing”. The third most costly reduction of 1 m^3/year of water supply is in SK-SRB.

Interestingly, reducing water in the NSRB regions, i.e., AB-NSRB and SK-NSRB, is more costly than restricting water supply in the SSRB regions. This can be partly explained by the fact that big water users such as “Irrigated crop and animal production” are mostly located in the SSRB regions. Water demand in the NSRB regions is mainly related to “Mining, quarrying, and oil and gas extraction” and “Manufacturing”, which incur the highest costs as a result of a water restriction, and hence are largely responsible for the higher costs in the NSRB regions. In Figure 4.5, irrigated and rain-fed crop and animal production sectors are ranked as the least influential levers. This can be attributed to the relatively larger amounts of water used by these sectors for their output production compared with the other water-use sectors in the SaskRB.

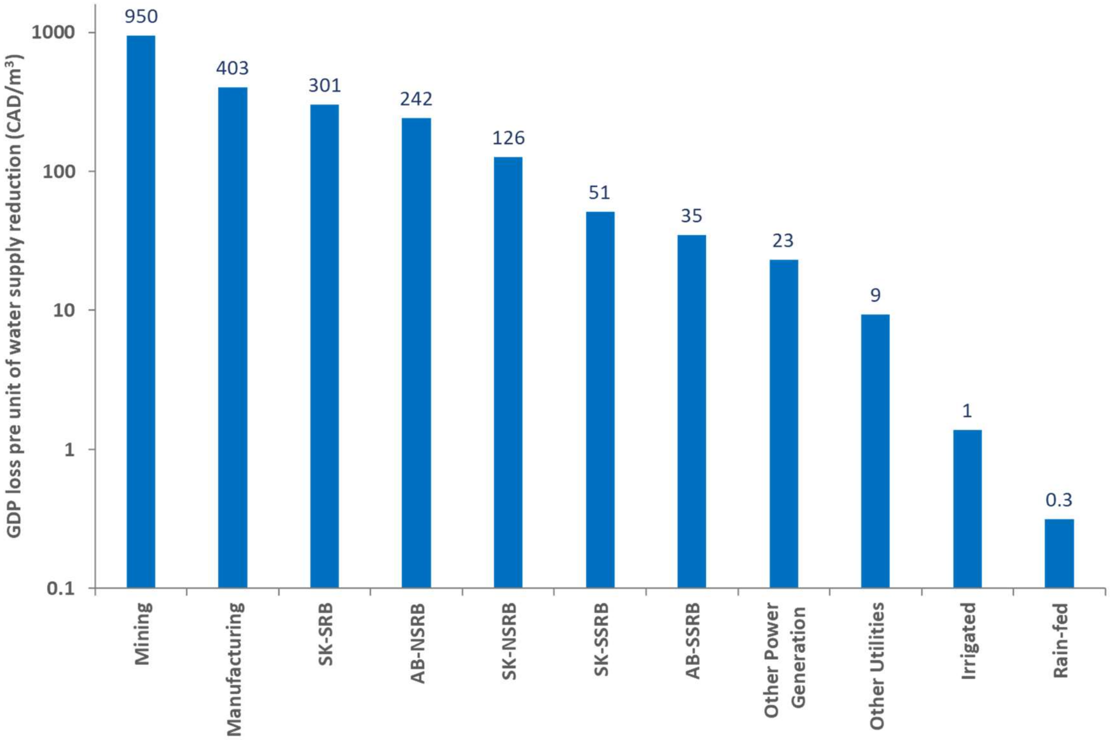


Figure 4.5. Ranking of total economic losses in the whole Saskatchewan River Basin related to sectoral and regional decision levers (horizontal axis) based on an absolute reduction in water supply (m^3/year)

4.4.2. Stress Test of Alternative Water Allocation Strategies

Table 4.2 presents the loss of GDP in the SaskRB as a whole in response to different water allocation strategies (current allocation and economically optimal allocation) related to water availability restrictions imposed on the river basin economy in 2015 varying between 10% and 90% (scenario's 1 to 9). The economic loss estimated through the reduction in SaskRB's GDP is substantially lower when an economic approach is applied to minimize losses in GDP and allocate water to those sectors and regions where a water availability reduction influences gross output most, especially when water shortages increase. Economic losses by using an economic optimization approach under water scarcity can be reduced between 28% and 79% compared to the current water allocation strategy used in the SaskRB. The relative change in GDP loss in this study is non-linear and disproportionate under the current water allocation strategy. The relative decrease in the basin's GDP is systematically higher under the current water allocation strategy, varying between 21 and 112% depending on the reduction in water availability (from 70 to 80%

and from 10 to 20%, respectively), except for the reduction of water availability from 80 to 90%. In the latter case, the relative loss in GDP (8.6%) is slightly lower than the relative reduction in water supply (12.5%). For example, reducing water from 10 to 20% (a reduction of 100%) results in a loss of GDP of 2,835 million CAD (5,375 – 2,540 million CAD), which is equivalent to a loss of 112%. Under the economically optimal allocation, however, a relative reduction of water availability yields the same relative reduction in GDP under the first two scenarios but a slightly higher reduction in GDP under scenarios 3 to 7. By reducing 80 and 90% of water availability, the relative loss of GDP experiences a sharper disproportionate increase than the relative decrease in water availability under this allocation strategy.

Table 4.2. Total loss of Gross Domestic Product in 2015 prices in the Saskatchewan River Basin economy under different water availability reductions and water allocation strategies

		Water Allocation Strategy			
		Existing allocation		**Economically optimal allocation**	
Scenario					
0	Baseline GDP: Million CAD 320,884	**10^6 CAD**	**%**	**10^6 CAD**	**%**
1	10% reduction in water availability	-2,540	-0.79	-1,822	-0.57
2	20% reduction in water availability	-5,375	-1.67	-3,644	-1.14
3	30% reduction in water availability	-9,979	-3.11	-5,481	-1.71
4	40% reduction in water availability	-19,519	-6.08	-7,477	-2.33
5	50% reduction in water availability	-31,009	-9.66	-9,623	-3.00
6	60% reduction in water availability	-45,415	-14.15	-11,806	-3.68
7	70% reduction in water availability	-66,462	-20.71	-14,071	-4.38
8	80% reduction in water availability	-80,532	-25.10	-17,792	-5.54
9	90% reduction in water availability	-87,424	-27.24	-21,594	-6.73

To further explore different patterns in the results, Figure 4.6 illustrates the changes in sectoral water supply and gross output under the different water availability reduction scenarios and the two allocation strategies. Both allocation strategies reduce water from “Irrigated crop and animal production”. However, this reduction is relatively smaller under the existing water allocation strategy for all scenarios except Scenario 9 compared to the optimal allocation. This can be attributed to the fact that the current strategy allocates water according to the priorities of demands. As such, water is supplied first to irrigation demands with higher priorities than other non-irrigation demands. This is the case, for example, for senior license-holder irrigators in Alberta. The economically optimal allocation strategy, on the other hand, reduces more water from irrigation and allocates this water to other water-use sectors where reducing water is more costly than reducing water from irrigation.

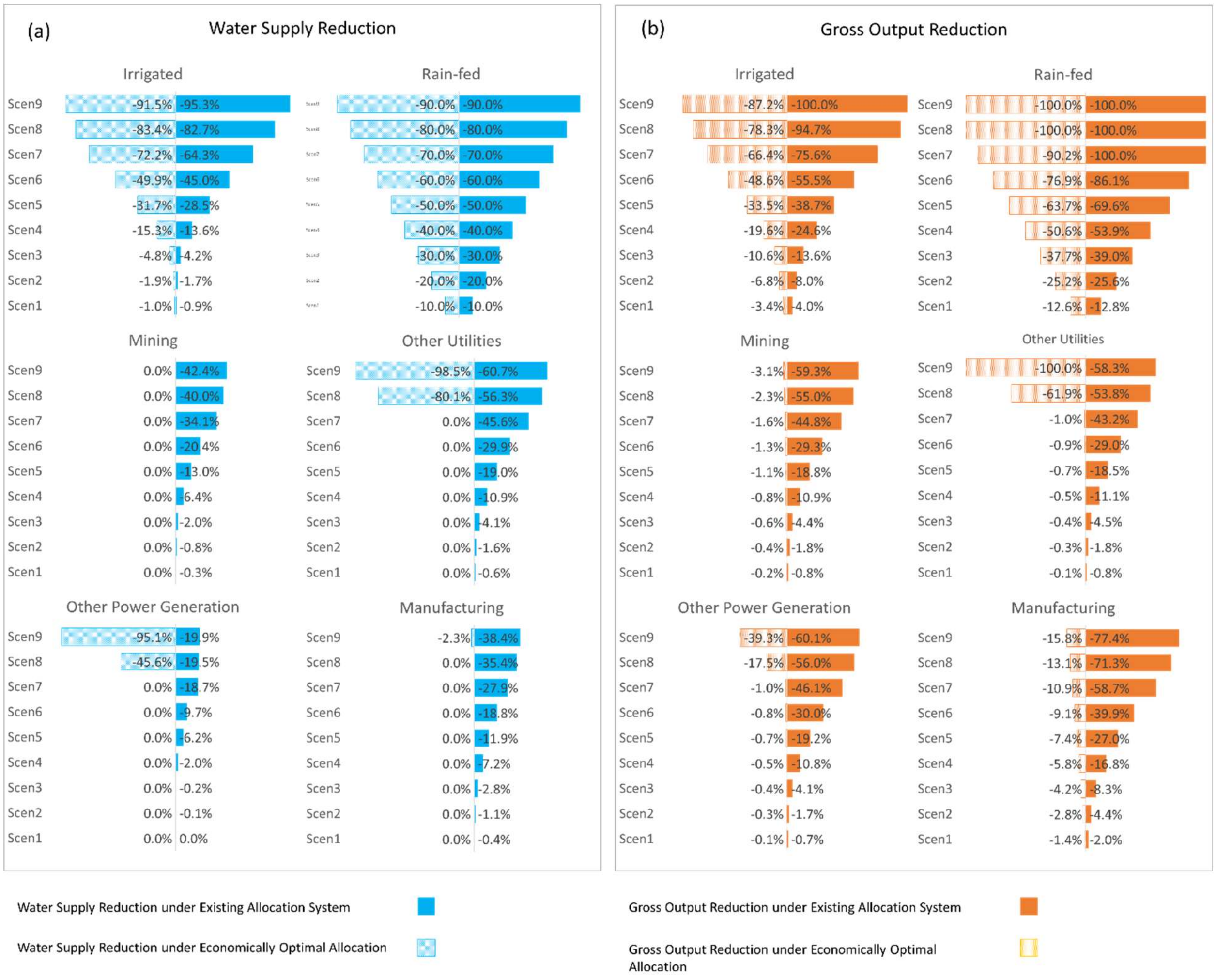
Interestingly, however, the output of “Irrigated crop and animal production” suffers less under the economically optimal strategy which can be explained by the fact that the increase in output of other water-use sectors offset a part of the reduction in irrigation’s output. This can also be observed in the output of “Rain-fed crop and animal production” under the optimal allocation strategy under scenarios 1 to 7. These results do not suggest that water can be replaced by other inputs in the production process of the crop and animal production sector. Rather it shows that under the existing allocation, the output of sectors such as “Manufacturing” and “Mining, quarrying, and oil and gas extraction” that provide inputs to agriculture decreases considerably higher than under the economically optimal allocation. This causes the output of agricultural sectors (both irrigated and rain-fed crop and animal production) to drop more under the existing water allocation strategy.

Another related result here is that reductions in sectoral gross output under different scenarios are disproportionate to the reductions in their water supply. This can also be explained by the interconnectedness among different sectors. For example, under the first scenario, Irrigated and Rain-fed crop and animal production are the only sectors from which water is reduced. However, the output of these two sectors decreased disproportionately to the amount of reduction in their water supply. This means a 3.4 and 12.6% reduction in gross output of Irrigated and Rain-fed crop and animal production, respectively, due to 1 and 10% reductions in their water supply, respectively. In this case, the disproportionate reduction in gross output is basically associated with the interconnectedness between these two sectors. Part of the production of rain-fed crop and animal production goes to irrigated crop and animal production as part of its input and vice versa. Therefore, reductions in the output of each sector exacerbate the decrease in the output of the other one under this scenario.

The optimal allocation strategy fulfills the water demand of all sectors, except “Rain-fed crop and animal production”, up to a 70% reduction in water availability by only restricting water supply to “Irrigated crop and animal production”. As shown in Figure 4.6(b), under scenarios 1 to 7, all sectors other than rain-fed and irrigated crop and animal production experience only small reductions in their output due to their economic transactions with these agricultural sectors. By reducing water availability further to 80%, also “Other utilities” and “Other power generation” start losing a part of their water supply and, consequently, their output, i.e., 61.9 and 17.5%, respectively. As can be seen in Figure 4.6, by reducing 80% of the water from Rain-fed crop and animal production, this sector losses all its output which explains the sharp increase in the economic loss of the entire SaskRB under this scenario and Scenario 9 as shown in Table 4.2.

Although water supply to all sectors except rainfed and irrigated crop and animal production remains largely unchanged, the gross output of these sectors still decreases under the economically optimal water allocation strategy. For example, gross output in “Manufacturing” decreases from 1.4% (Scenario 1) to 15.8% (Scenario 9) under this allocation strategy although water supply to this sector only decreases by 2.3% under the last scenario. The economically optimal allocation strategy also fulfills the water demand of “Mining, quarrying, and oil and gas extraction” under all nine water availability reduction scenarios. However, this sector still loses some of its output, i.e., from 0.2% to 3.1% (Figure 4.6(b)). Also, “Other utilities” and “Other power generation” are other sectors that experience a reduction in their output without any reduction in their water supply under scenarios 1 to 7 (Figure 4.6(a)). The reduction in all these sectors’ output can be attributed to the interconnectedness of the different sectors. Reducing water in irrigated and rainfed crop and animal production causes their gross output to fall, and this reduction in output propagates to the rest of the economy based on the interconnection (the multiplier effects) between these directly affected sectors and other sectors.

The effect of allocating water based on economic considerations on the economy of the river basin as a whole can also be seen in Figure 4.6. By fulfilling the water demand of sectors whose water availability reduction is most influential on the economy, such as “Mining, quarrying, and oil and gas extraction” and “Manufacturing”, the economically optimal allocation strategy imposes a much lower burden on the output of all sectors. This leads to a lower total economic loss under this allocation strategy as shown in Table 4.2.



Note: the names of some sectors have been shortened. Irrigated: Irrigated crop and animal production; Rain-fed: Rain-fed crop and animal production; Mining: Mining, quarrying, and oil and gas extraction.

Figure 4.6. The percentage changes in (a) sectoral water supply and (b) gross output under different water availability reduction scenarios and water allocation strategies

4.5. Discussion and Conclusions

By identifying the most influential decision levers and investigating the economic response of alternative water allocation strategies under water availability restrictions, this study attempts to inform decision-makers about the economic vulnerability of the SaskRB to water (re)allocation among competing use(r)s under water scarcity conditions. The integrated hydro-economic model developed in this study allows us to evaluate the direct and indirect economic impacts of changes in water availability while simulating the water resource and demand interactions in a regulated multi-jurisdictional river basin under plausible future conditions. The outcomes generated with the help of this hydro-economic model serve as a building block for finding sustainable and robust strategies to efficiently manage the limited water resources in times of scarcity. Understanding the direct and indirect short-term effects of water allocation decisions on the river basin economy as a whole, connecting sectors and regions simultaneously, supports the identification of robust and sustainable water allocation strategies under water stress. The novelty in the study was the systematic analysis of both sectoral and regional decision levers. This allowed us to identify not only in which sectors it would be least costly to reduce water supply but also in which sub-basin.

Our findings indicated that including economic criteria in allocating water would considerably mitigate the economic losses in the face of future water shortages. Taking into account in which sector and in which sub-basin reducing water supply is least costly compared to the current water allocation strategy in the SaskRB, we showed that such a strategy could reduce the economic loss of water stress in the economy as a whole by up to 82%, i.e., about 66 billion CAD in 2015 prices. It is assumed here that there are no additional costs in reallocating resources to generate gross output under the imposed water supply restrictions. For example, labor is considered to be completely mobile between different economic sectors. It should be noted that in this study, we focused only on the changes in the gross output, while the impacts of water shortages can also be investigated from other perspectives, including food security and employment.

The integrated hydro-economic model includes rain-fed agriculture along with other main water-use sectors that receive water from surface water resources. Our findings indicated that neglecting the impacts of water stress on rainfed agriculture, we are likely to underestimate the impacts of water shortages on the economy as a whole in the river basin. Considering rainfed agriculture in this study helped to increase our understanding of the interrelationship between rainfed agriculture and the rest of the economy and how the inclusion of both rainfed and irrigated agriculture as the biggest water users can help to investigate the economic impacts of water shortages. The study revealed that the tradeoffs to mitigate the expected economic losses under future water scarcity in the river basin would be by reducing water supply to the agriculture sector.

No detailed sectoral data are available with respect to alternative sources of water supply in the SaskRB such as groundwater, poor-quality water, or recycled water. This means that we were unable to include these sources in the integrated model and quantify the impact of using additional substitution possibilities as another strategy on the economy of the river basin. Alternative sources, in particular, can be used to supply parts of the water demand of industries that do not necessarily need freshwater. According to Statistics Canada (2020a), in 2017, 30%, 43%, and 22% of the water intake in manufacturing industries in Alberta, Saskatchewan, and Manitoba, respectively, were supplied from sources other than surface freshwater, including groundwater and saline water sources. Furthermore, in the same year, 448 MCM of the total amount of water used by the manufacturing industry in the three provinces sharing the SaskRB was reported as recirculated water (Statistics Canada, 2020b). These statistics suggest that potential alternative sources of water could play an important role to reduce the increasing pressure on the river basin's fresh surface water resources.

This study attempts to inform decision-making about finding sustainable and robust water allocation strategies in the face of future water shortages. Although the study does not adopt a robust decision-making framework that tests the robustness of different strategies across a wide range of futures, it can inform the process of robust decision-making about the most vulnerable sectors and regions to changes in water availability. The distribution of the economic impacts across different sectors and regions and the relative importance of these impacts provide valuable insight to support articulating alternative water allocation strategies to mitigate the economic consequences of droughts in the future. Using these economically relevant strategies as alternative solutions helps to reduce the computational burden of testing the robustness of multiple strategies across a wide range of future scenarios in the RDM process.

The economically optimal water allocation strategy here is aimed at minimizing the economic loss in the entire SaskRB under water stress. This means that water is first and foremost supplied to sectors and regions where reducing water would generate the highest economic cost, regardless of other considerations, such as food or energy security or environmental considerations. This was only possible by adopting an integrated water management approach under the assumption that such a strategic river basin plan can be prepared for the SaskRB in times of drought to mitigate the economic consequences. Although the SaskRB is multi-jurisdictional and each province sharing this river basin has its own water allocation strategies based on local and regional economic and political concerns, several attempts towards integrated water resources management have been made, including the establishment of the Prairie Provinces Water Board in 1969 for transboundary water management.

These attempts suggest that there is interest in preparing an integrated water management plan for the entire river basin to face future droughts. However, such an integrated plan will have to account for and accommodate potential conflicts of interest among different water uses and users within and between regions, including tradeoffs between environmental and economic objectives and the potential impacts of water re-allocation on employment and provincial and regional food and energy security.

The present study, however, was explicitly focused on the impacts of water (re)allocation strategies on the economic output of the SaskRB. Being mindful of the possible impacts of water (re)allocation on other social, environmental, and even political interests, as mentioned above, decision-makers can use the findings of this study as insightful benchmarks to better understand the distribution of the economic impacts among the sectors and regions making up the SaskRB economy, and the relative importance of these impacts in different parts of the economy of this transboundary river basin. This provides decision-makers with valuable insight into the possibility of (substantially) reducing the economic costs of future water stress by shifting from the existing priority-based water allocation system to a water allocation system based more on economic considerations, as, for example, shown in this study.

Author Contributions

LE and RB conceptualized the method. LE developed the model, wrote the computer codes, designed and performed the experiments. LE, RB, and SR contributed to the interpretation of the results. LE wrote the paper. RB and SR contributed to the editing of the paper.

Appendix 4-A

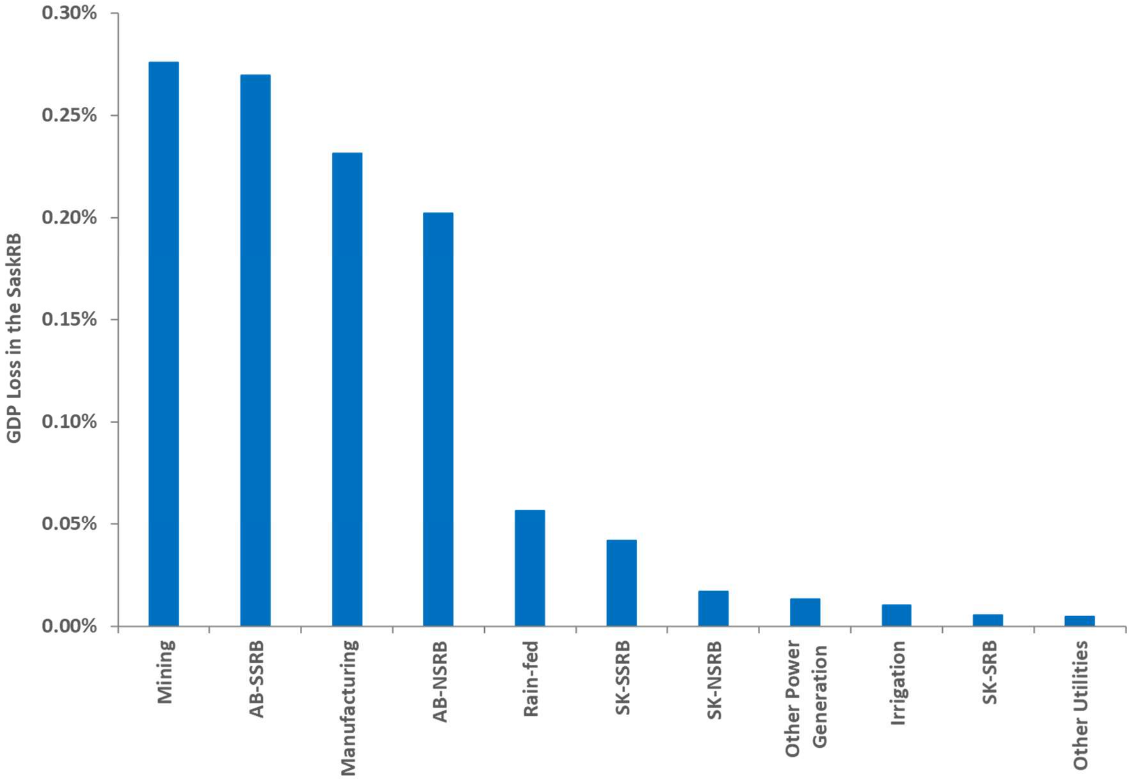


Figure 4-A-1. Ranking of GDP losses in the whole Saskatchewan River Basin related to sectoral and regional decision levers (horizontal axis) based on 1% reduction in water supply

Chapter 5

Comparing the Applicability of Hydro-Economic Modelling Approaches in Large-Scale Decision-Making for Multi-Sectoral and Multi-Regional River Basins

Eamen, L., Brouwer, R., and Razavi, S. (Under revision). Comparing the Applicability of Hydro-Economic Modelling Approaches in Large-Scale Decision-Making for Multi-Sectoral and Multi-Regional River Basins. *Environmental Modelling and Software*.

Abstract

A popular approach to hydro-economic modelling is to connect a detailed water resources system model with a simple economic component, e.g., the quantity of production times market prices. Another approach is to embed water quantity data in a detailed economic model, e.g., computable general equilibrium or input-output models. Only a limited number of studies attempt to couple detailed models from both water and economic systems to create an integrated hydro-economic model. This chapter compares the application of these three modelling approaches in evaluating economic impacts in a transboundary river basin. Hydro-economic models are developed for the multi-jurisdictional Saskatchewan River Basin in Canada to estimate the economic impacts of climate change and socioeconomic development scenarios. Findings indicate that although the integrated model is challenging to develop, its results are most relevant in the water allocation context owing to capturing the economic sectoral/regional interdependencies and features of the water system.

5.1. Introduction

Economic criteria and principles have been incorporated in water management practices since the mid-twentieth century (Lund et al., 2006; Harou et al., 2009) using hydro-economic models as frameworks that integrate water and economic components (Heinz et al., 2007; Brouwer and Hofkes, 2008; Harou et al., 2009). A popular approach to hydro-economic modelling in water resources management is the engineering-based approach. These models are based on a detailed representation of the water component, e.g., node-link networks, and a partial equilibrium (i.e., only accounting for one sector or one part of the economy without considering their interdependencies with the other parts) representation of the economic component, e.g., an estimation of changes in sectoral production multiplied by an average market price (e.g., Gillig et al., 2001; Cai et al., 2003; Jenkins et al., 2004; Medellín -Azuara et al., 2007; Harou et al., 2010; Razavi et al., 2013; Graveline et al., 2014; Ward, 2014; Esteve et al., 2015; McCarl et al., 2015; Nguyen et al, 2016; Basheer et al., 2018; Mirchi et al., 2018; Amjath-Babua et al., 2019; García et al., 2019; Geressu and Harou, 2019; Payet-Burin et al., 2019; Do et al., 2020). Having a detailed representation of the water system, these models simulate the internal interactions of different elements in this system - e.g., among water resources and demand sites - reasonably well. Their economic representation, however, accounts for only a part of the economy without considering its interactions with the other parts. This economic representation can solely assess the economic impact of changes in the water system on directly affected sectors or regions, while, in reality, this impact does not remain in that very sector (region). It propagates to the rest of the economy through the economic transactions between other sectors (regions) and the directly affected sector (region).

Another group of hydro-economic models is the economic-based model using macro-economic approaches, including general equilibrium and input-output analysis, with a simplified representation of the water component, e.g., embedded water use or water quality data (e.g., Duarte et al., 2002; Gómez et al., 2004; Velázquez, 2006; Brouwer et al., 2008; Strzepek et al., 2008; Calzadilla et al., 2010; López-Morales and Duchin, 2011; Antonelli et al., 2012; Juana et al., 2012; Cazcarro et al., 2013; Zhang and Anadon, 2014; White et al., 2015; Lutter et al., 2016; Levin-Koopman et al., 2017; Ridoutt et al., 2018; Almazán-Gómez et al., 2019; Teotónio et al., 2020). Although these models capture the interactions between different sectors and actors in the economy, they lack a mechanism to simulate the interactions of different features in the water system. Often all that flows in these models is money, not water. Water characteristics are represented in a very superficial way, which can lead to errors in decision-making. These models do not account, for example, in any detail for the role specific hydrological and/or eco-morphological features or elements in a river basin play, such as regulating infrastructures (e.g., reservoirs), etc. that affect water supply to different sectors. Lacking such a mechanism prevents the economic-based models from simulating the changes in their water component (water-related dataset) due to different alterations in the water system that are imposed by drivers such as climate change, socio-economic development, and policy interventions.

In addition to these hydro-economic modelling attempts, a limited number of studies couple detailed water and economic components to create an integrated hydro-economic model (e.g., Jonkman et al., 2008; Dellink et al., 2011; Kahsay et al., 2019; Knowling et al., 2020; Tanoue et al., 2020). Although these models can be extremely data-demanding (compared with the two former approaches), they capture the interactions between elements of both economic and water systems.

Regardless of their structural configuration, hydro-economic models have been used in a variety of water quality and water quantity applications, such as evaluating economic impacts of climate and socioeconomic changes, assessing economic consequences of water management decisions/policies, and identifying economically efficient water management strategies. One of the most important decisions in water management often is allocating scarce water resources among competing uses. Decision makers, therefore, need to be informed about the consequences of their allocation decisions under different future conditions, particularly in river basins with competing water uses. Hydro-economic models have been applied to assess the economic consequences of water allocation strategies (e.g., Cai and Rosegrant, 2004; Blanco-Gutiérrez et al., 2013; Llop, 2013; MacEwan et al., 2017; Almazán-Gómez et al., 2019; Cazcarro et al., 2020). However, many if not most of the hydro-economic models developed for this purpose consist of a more detailed representation of either water or economic system and a simplified representation of the other system. This is more evident in the number of relevant scientific publications. For example, without the intention of being complete, searching the journals Environmental Modelling & Software (EMS) and Water Resources Research (WRR) for the topic "water allocation" based on "economic" criteria in the 2010-2020 period yielded 52 publications, of which only one study in

EMS used an integrated approach by linking engineering and economic models (i.e., Kahsay et al., 2019). The rest of these studies applied engineering-based hydro-economic models with one study in WRR that used an economic-based approach, i.e., general equilibrium with an embedded set of water-related data (i.e., Luckmann et al., 2014).

Although the need to take an interdisciplinary approach to water resources management problems is widely recognized (e.g., Croke et al., 2007; Cai, 2008; Ward, 2009; Wheater and Gober, 2013; Lund, 2015; Vogel et al., 2015; Loucks and van Beek, 2017; Badham et al., 2019), these statistics show that a limited number of studies has attempted to bring detailed representations of the two disciplines together in the water resource management scientific community. This motivates us to investigate the relevance and applicability of different hydro-economic modelling approaches as decision support tools in transboundary river basins. In this chapter, therefore, engineering, economic, and integrated hydro-economic models are developed and used to evaluate the impacts of climate change and socioeconomic development on a multi-sectoral and multi-regional river basin. Although several studies have evaluated the impacts of climate change (e.g., Levin-Koopman et al., 2015) and socioeconomic development scenarios (e.g., Kahsay et al., 2017) using hydro-economic models, most of them applied only one modelling approach and did not benchmark that against other approaches.

The engineering-based model developed in this study consists of a water resources system model and an economic component that estimates the sectoral quantity of production and the corresponding benefits. The economic-based model is an inter-regional supply-side input-output (ISIO) model embedding a set of water supply data. Finally, the integrated model is created by linking the water resources system model and the ISIO model. The application of these three models is illustrated using the Saskatchewan River Basin (SaskRB) in Canada as a case study. Spanning three Canadian provinces, this river basin is home to 75 percent of irrigated agriculture of Canada (Statistics Canada, 2018i). Potash mining and oil and gas extraction are among other main water-use economic activities in this river basin. The multi-sectoral and multi-jurisdictional nature of the SaskRB allows investigating the importance of considering cross-sectoral and inter-regional connectedness in hydro-economic modelling, particularly when applied as a decision support tool.

In addition to the three hydro-economic model configurations, we consider two timeframes with different climatic conditions. This stems from the fact that the economic components used in this study (either for the engineering model or the ISIO model) are based on economic data for a certain year. Consequently, the developed models represent the economic structure under the climatic conditions of the models' base year. We, therefore, develop the models for the two most recent years under different climatic conditions (i.e., wet and dry climates) for which the economic data were available. As explained in Chapter 3, climatic conditions here refer to the amount of available water, i.e., precipitation and surface freshwater, in a certain year. This helps investigate the performance of the models based on the economic structure affected by different climatic conditions. The applicability of the models is examined under two types of scenarios, namely climate change and socioeconomic development scenarios. The economic changes due to alterations in the quantity of water supply to different economic sectors under these scenarios are evaluated using the three hydro-economic models. This is among a few attempts to examine the relevance of these modelling approaches in the transboundary river context by comparing their performance under different scenarios. The findings of this chapter, therefore, shed light on the applicability of different hydro-economic modelling approaches in assessing the economic impacts of water availability changes due to climate change, socio-economic development, and policy measures. This is critical when these models are applied to support large-scale decision-making in multi-sectoral and multi-regional river basins such as the SaskRB.

5.2. Case study

The three hydro-economic models developed and applied in the present chapter are elaborated in this section using the Saskatchewan River Basin as a case study.

The Saskatchewan River Basin and its hydro-economic regions introduced in the previous chapters are shown in Figure 5.1.

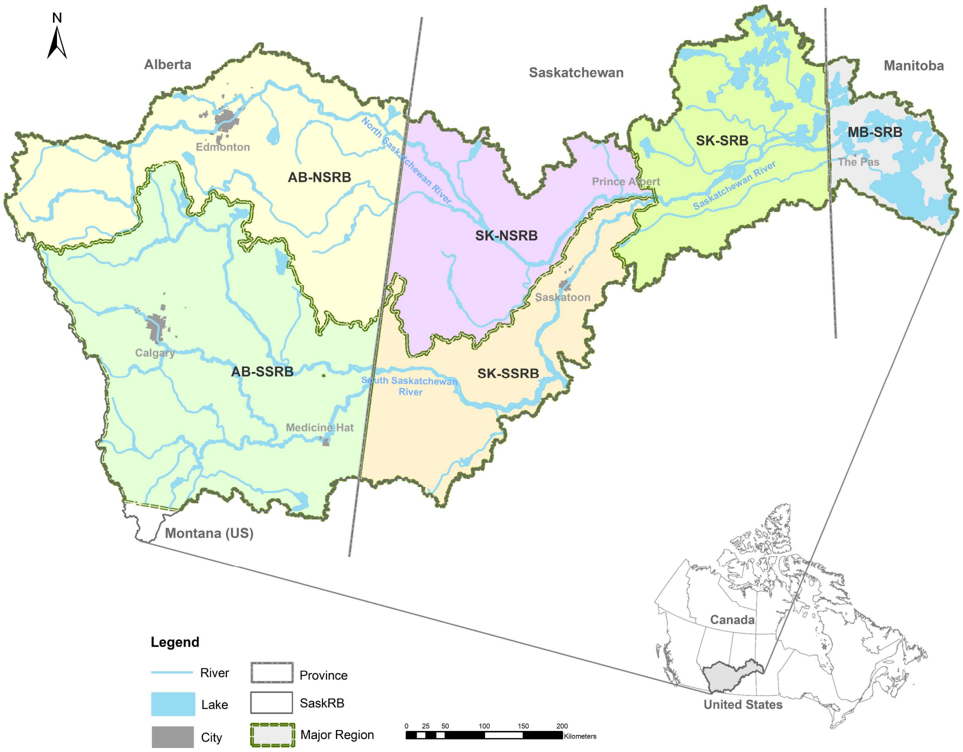


Figure 5.1. The Saskatchewan River Basin, its three Canadian provinces, and six hydro-economic regions

The years 2014 and 2015 (the study years hereafter) were selected to be investigated in this chapter as the most recent years with different climatic conditions (represented by water availability) for which the economic data were available at the time of this study. Selecting these wet (2014) and dry (2015) years allows us to study the response of the hydro-economic system of this river basin to changes in water availability under both climatic conditions. To make the economic results of the two years comparable the IO tables for 2014 were converted into Canadian dollar values of 2015 using the GDP deflator for each province (Statistics Canada, 2019b). Table 5.1 presents the water supply and production of irrigation and other water-use sectors in the SaskRB in the years 2014 and 2015.

Table 5.1. Water supply to and production of irrigation and other water-use sectors in the hydro-economic regions of the Saskatchewan River Basin in the years 2014 and 2015

Regions	Water Supply (MCM)		Production (million CAD)	
	2014 (Wet)	2015 (Dry)	2014 (Wet)	2015 (Dry)
Irrigation				
AB-NSRB	10	11	7	9
AB-SSRB	1863	2199	1453	1828
SK-NSRB	19	23	9	12
SK-SSRB	165	194	48	61
SK-SRB	1.4	1.7	0.7	0.9
MB-SRB	0	0	0	0
Other Water-Use sectors				
AB-NSRB	4577	3513	75415	63480
AB-SSRB	21642	18823	103213	84692
SK-NSRB	20	20	6900	5594
SK-SSRB	8469	4935	15851	13407
SK-SRB	34509	24490	2061	1740
MB-SRB	54639	33545	113	112

Note: other water-use sectors include all sectors other than the irrigation sector that receive raw water from the Saskatchewan River, including “Mining, quarrying, and oil and gas extraction”, “Utilities”, and “Manufacturing”.

According to Table 5.1, water supply to the irrigation sector was higher in 2015 than in 2014 due to the hot and dry cropping season of the year 2015. Comparing the production of this sector in these two years indicates that the monetary value of production increased between the two years although the amount of irrigated production in physical units declined from 2014 to 2015 due to the climatic conditions. This can be attributed to the increase in the annual prices for major crops in 2015 (ICDC, 2014 and 2015; Government of Alberta, 2014 and 2015; Alberta Agriculture and Forestry, 2016).

As can be seen in this table, both the water supply and production of the other water-use sectors decreased from 2014 to 2015, which can be explained partially by the decline in the price of oil and potash and the low sales of manufacturing production in 2015 (Government of Alberta, 2016 and 2017; Government of Saskatchewan, 2016).

5.3. Hydro-economic modelling approaches and their comparability

As mentioned earlier, three configurations of hydro-economic models were developed in this chapter, namely engineering-based, economic-based, and integrated hydro-economic models. The water resources system model developed for the SaskRB by Shah et al. (under review) was used here in engineering and integrated models. This model is a node-link model developed for the sub-basins of the SaskRB in MODSIM-DSS, including 174 irrigation demand nodes, 232 non-irrigation demand nodes, 58 storage reservoirs, and 30 hydropower plants. The economic component of the economic and integrated models is based on an economic input-output approach and that of the engineering-based model is based on the common practice approach in engineering studies, which is estimating the quantity of production and multiplying it by average market prices. The three hydro-economic models for the SaskRB are outlined below.

5.3.1. Developing an Engineering-Based Hydro-Economic Model

This model consists of the water resources system model and an engineering economic impact assessment component. In this study, we focused on irrigation as the main water consumer in the SaskRB. Therefore, the economic component estimates the amount of sectoral production through a crop yield function and multiplies this amount by the market price and revenue minus costs of the unit of production to estimate the sectoral output and the net benefit, respectively. In crop yield estimation, we assume that the cultivation conditions, including soil, crop type, cultivation techniques, etc. are identical for all regions, and hence the yield (Y_i) for the crop i is considered to be only a function of water availability (W_i).

$$Y_i = f(W_i) \tag{5.11}$$

This assumption has implications for the results. However, in the absence of reliable data, it is common practice that modelers consider such assumptions in their works (e.g., Ben-Gal et al., 2013; Hassanzade et al., 2014). We used the crop yield equation proposed by FAO (Doorenbos and Kassam, 1979; Allen et al., 1998; FAO, 2012) to define the above function. We defined W_i as:

$$W_i = \frac{ET_a}{ET_c} \tag{5.12}$$

where, ET_a is the actual crop evapotranspiration and ET_c is the maximum evapotranspiration. ET_a is considered here as the amount of water that is actually provided for the crop. ET_c was calculated through $ET_c = ET_0 \times K_c$, in which ET_0 is the reference evapotranspiration in mm and K_c is the crop coefficient. ET_0 was estimated here on a daily basis using the modified Hargreaves equation (Droogers and Allen, 2002) that was calibrated for the SaskRB as:

$$ET_0 = \alpha \times 0.408RA \times \left(T_{avg} + 17\right) \times (TD - 0.0123P)^{0.76} \tag{5.13}$$

where RA is extraterrestrial radiation in (MJ m^{-2} d^{-1}), T_{avg} is the average of the mean maximum and mean minimum temperature in (°C), TD is the difference between the mean maximum and mean minimum temperature in (°C), and P is precipitation in mm. $\alpha = 0.000455$ is the calibration coefficient for the SaskRB and was calculated using ET_0 estimates from Penman-Monteith method in Red Deer, Bow, Oldman, and South Saskatchewan sub-basins in Alberta and the South Saskatchewan sub-basin in Saskatchewan (Alberta Agriculture and Forestry, 2019). K_c for different stages of the growing season of various crops were obtained from FAO Irrigation and Drainage paper No. 56 (Allen et al., 1998). The growing season in most parts of the SaskRB starts in May and ends in September.

The yield response to water availability was then expressed as:

$$Y_i = Ym_i - Ym_i \times Ky_i(1 - W_i) \tag{5.14}$$

in which Ym_i is the maximum crop yield and Ky_i is yield response factor for crop i that represents the relationship between changes in water use and consequent crop yield losses. Ky_i for several crops has been derived and presented by FAO (e.g., Doorenbos and Kassam, 1979; FAO, 2012). The monetary production ($Prod_i$) and Net benefit (NB_i) for crop i were then estimated as:

$$Prod_i = Y_i \times Price_i \tag{5.15}$$

$$NB_i = Y_i \times (Price_i - Cost_i) \tag{5.16}$$

where $Price_i$ and $Cost_i$ are the total price and total cost of the unit of production for crop i, respectively.

Due to limited data availability for private irrigators in Alberta and Saskatchewan, crops were grouped to make the crop mix, meaning that the crop mix in each province consists of various groups of crops rather than individual crops. Then, one crop, which is usually the dominant cultivated crop in its group, was selected as the representative of that group of crops. The calculations thereafter were implemented based on the characteristics of the representative crop of each group. This method facilitates the calculation process in the absence of reliable data, particularly in the case of private irrigators. Crop groups and their representative crops in Alberta and Saskatchewan are presented in Table 5.2. It should be noted that there is no irrigated agriculture in the Manitoba portion of the SaskRB.

Table 5.2. Crop groups and their representative crops in Alberta and Saskatchewan

Province	Crop Group	Representative Crop
Alberta	Cereals	Wheat
	Forages	Alfalfa
	Oilseeds	Canola
	Specialty Crops	Potato
Saskatchewan	Cereals	Wheat
	Forages	Alfalfa
	Oilseeds	Canola
	Pulses	Lentil
	Specialty Crops	Potato

To be consistent with the other two hydro-economic models, the engineering approach was applied using the costs and prices for the years 2014 and 2015 released by Irrigation Crop Diversification Corporation (ICDC) (2014 and 2015) and the Government of Alberta (2014 and 2015) in Saskatchewan and Alberta, respectively. Total costs of crops include the costs of seed, fertilizer, chemicals, equipment fuel and repair, irrigation power and repair, irrigation water charge, crop and hail insurance, machinery and building repair, irrigation and non-irrigation machinery, custom work, hired labor, etc.

5.3.2. Developing an Economic-Based Hydro-Economic Model

This hydro-economic model is an inter-regional supply-side input-output (ISIO) model based on annual IO tables and embedding sectoral water supply data. The supply-side input-output model, originally proposed by Ghosh (1958) based on the Leontief input-output model (Leontief, 1936 and 1970), estimates the direct and indirect economic impacts of exogenous supply changes to the economy. This model is based on observed economic data collected on an annual basis in supply and use or input-output (IO) tables and the following equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{H}^{\mathrm{T}}\mathbf{C})^{-1}\tilde{\mathbf{v}} \tag{5.17}$$

where $\mathbf{x}$ is a vector of gross sectoral output, $\mathbf{I}$ is an identity matrix, $\mathbf{H}^{\mathrm{T}}$ is a transposed matrix resulted from dividing the use matrix by the total outputs of commodities, $\mathbf{C}$ is a matrix resulted from dividing the supply matrix by the total output of industries, and $\tilde{\mathbf{v}}$ is the vector of the sectoral value added. IO tables, however, are released at the provincial level and need to become compatible with hydrological boundaries, i.e., river basins. These tables, therefore, were first downscaled to sub-basin level. Then, the inter-regional IO matrices were created using intra- and inter-provincial trade flows, the labor force, and the population data. Finally, these IO tables were re-assembled to create the ISIO model for the entire river basin.

Water is embedded in the ISIO model as a primary input and hence a part of value added in Eq. 5.7. The value of change in the amount of water was defined here as:

$$\Delta\mathbf{v}_{\mathrm{w}} = \mathbf{p}\Delta\mathbf{w} \tag{5.18}$$

where $\Delta\mathbf{v}_{\mathrm{w}}$ is the value of change, $\mathbf{p}$ is the water productivity calculated as the amount of production per unit of water, and $\Delta\mathbf{w}$ is the change in the amount of sectoral water supply coming from the water resources system model. Therefore, we can estimate the changes in sectoral gross output ($\Delta\mathbf{x}$) as:

$$\Delta\mathbf{x} = \mathbf{G}\Delta\mathbf{v}_{\mathrm{w}} \tag{5.19}$$

For more detailed information on the methodology of developing the ISIO model see Chapter 2.

In this study, the IO tables of the SaskRB for the study years, i.e., the wet year 2014 and the dry year 2015, from Statistics Canada (2018a and 2019a) were used in developing the ISIO model. The results of the water resources system model of the SaskRB for the historical period were used as the sectoral water supply data embedded in this model. Water supply to different sectors in 2014 and 2015 was extracted from these results and fed into the ISIO model as the water data required to estimate the water productivity. The difference between this model and the integrated hydro-economic model is that in the ISIO model we only extracted a set of sectoral water supply data for certain years from the results of the water resources system model, whereas in the integrated model, the economic component (the ISIO model) is coupled with and remains connected to the water resources system model allowing us to simulate the scenarios from the water management perspective and estimate the sectoral water supply accordingly.

5.3.3. Developing an Integrated Hydro-Economic Model

This model was created by coupling the water resources system model and the ISIO model. Coupling the economic and water resources system models was challenging due to different resolutions and incompatibilities between these models and the associated datasets. ISIO is an annual model, whereas the water resources system model of the SaskRB works on a weekly basis. Spatially speaking, IO tables are at the provincial level, but the water resources system model is developed based on several demand nodes in different sub-basins. Finally, IO tables include 35 sectors (based on the Canadian System of National Accounts), including “Crop and animal production”, “Mining, quarrying, and oil and gas extraction”, “Utilities”, and “Manufacturing” that are considered main water-use sectors in this study. Other sectors receiving water from the “Utilities” sector are not individually accounted for here as the water exchange between these sectors and the “Utilities” sector is already captured in the IO tables. The demand nodes in the water management model, on the other hand, are simply divided into irrigation, non-irrigation, and hydropower nodes.

To address the different temporal resolutions of the models, the integrated model is considered to work on an annual basis. Therefore, the weekly results of the water resources system model, i.e., sectoral water supply, were aggregated to the annual scale. As described in Section 5.3.2, the ISIO model is an inter-regional model that downscales the provincial IO tables to the level of hydro-economic regions. To make the outcomes of the water resources system model compatible with this spatial resolution, the demand nodes of the same type in each hydro-economic region were aggregated to form a demand group of that type in each region. The process of these spatial down- and up-scaling is shown in Figure 5.2. As can be seen, for example, in Alberta, the provincial IO table was disaggregated to AB-NSRB, AB-SSRB regions, and the rest of the province to create the IO tables at a hydro-economic region scale (Figure 5.2(a)). As shown in part (b) of this figure, all irrigation demand nodes in the AB-SSRB were aggregated to one irrigation demand group at the hydro-economic region scale. The same process was implemented on the non-irrigation and hydropower demand nodes in this region and other hydro-economic regions of the SaskRB. The schematic of the integrated hydro-economic model of the SaskRB is presented in Figure 5.2(c). Note that these figures are prepared for illustrative purposes and do not include all details of the SaskRB water resources system model.

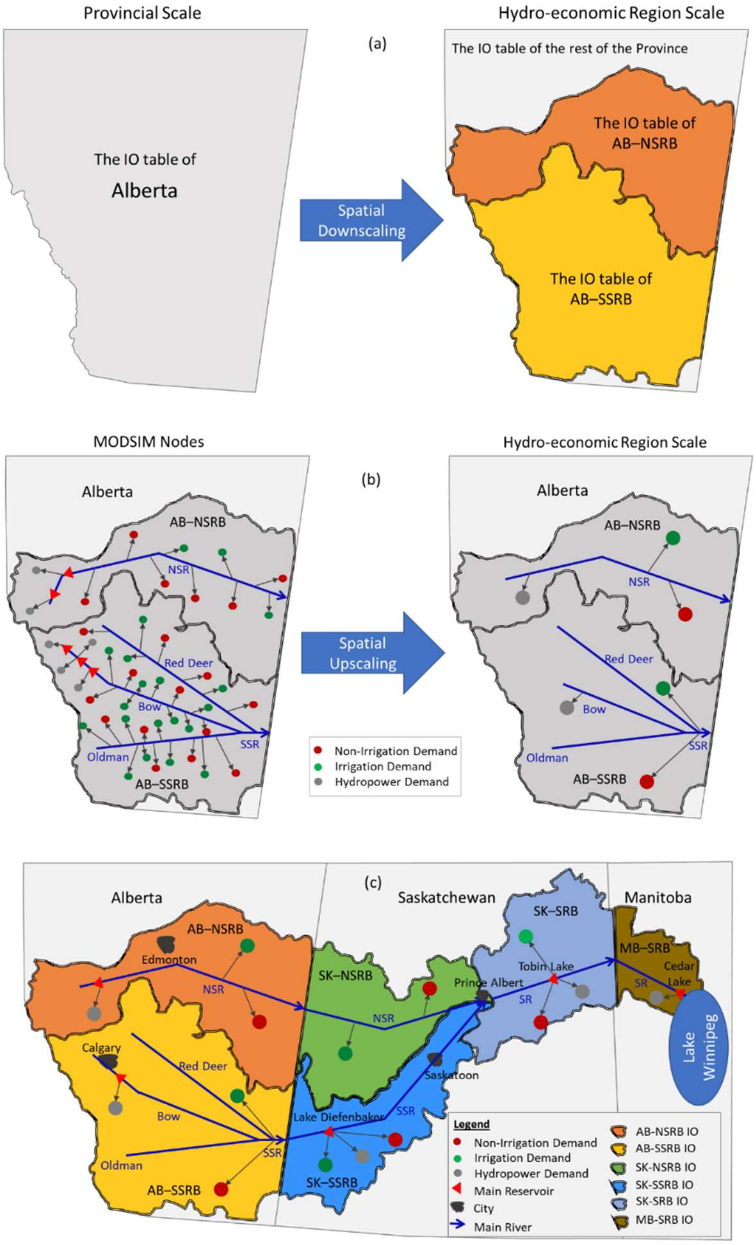


Figure 5.2. Examples of (a) spatial downscaling of IO tables and (b) spatial upscaling of MODSIM nodes, and (c) the schematic of the integrated hydro-economic model of the SaskRB

Finally, to deal with the different industry classifications of the two models, first, the “Crop and animal production” sector in the IO tables was divided into irrigated and rain-fed agriculture using the proportion of irrigated production to the area of irrigated lands (Chapter 2). Next, the electricity generation was separated from the rest of the “Utilities” sector in the IO tables – such as gas distribution, water and sewage, etc. – using the detailed level of these tables (Statistics Canada, 2018a and 2019a). The electricity generation was further split into hydropower and other power generation to become compatible with the water resources system model. Electricity, particularly in Alberta and Saskatchewan, is mainly generated in fossil fuel power plants. Hence, this separation was implemented proportional to the share of hydropower plants in generating electricity in each province, which is 3%, 14%, and 97% in Alberta, Saskatchewan, and Manitoba, respectively (CER, 2020). Then, the non-irrigation demand nodes from the water resources system model were disaggregated into mining, quarrying, and oil and gas extraction; other utilities; other power generation; and manufacturing to enable us to connect them with main water-use sectors from the ISIO model. This disaggregation is undertaken using the ratio of licenses of each sector to the total non-irrigation licenses in each major region. The industry classification of the two components of the integrated hydro-economic model and the final disaggregated level are shown in Figure 5.3. By addressing these challenges, we coupled the two models and created the integrated hydro-economic model for the SaskRB.

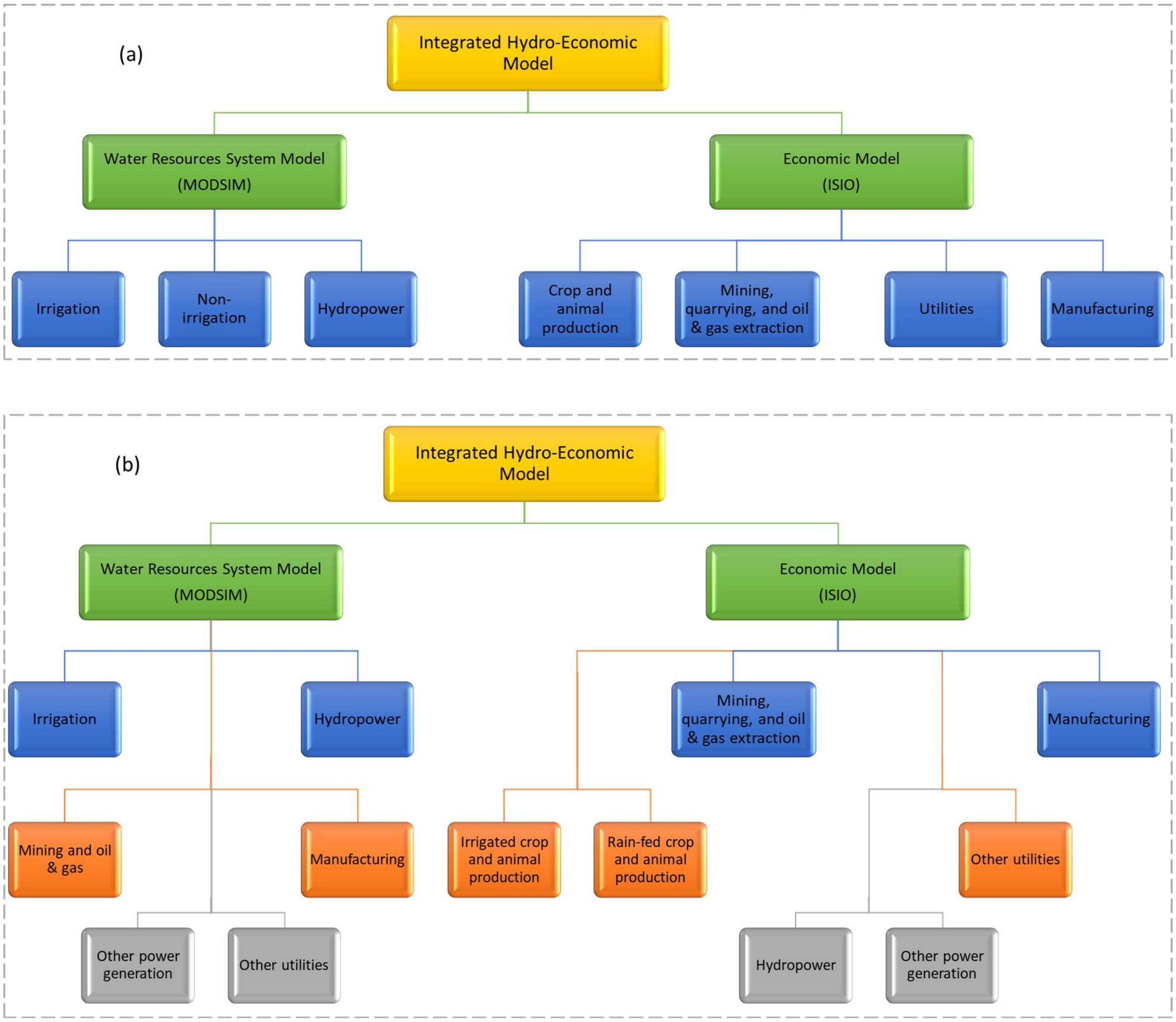


Figure 5.3. The industry classification of (a) the two components of the integrated hydro-economic model and (b) the final disaggregated sectors

5.3.4. Comparing the Structure and Workflow of the hydro-economic Models

Figure 5.4 illustrates the structure and workflow of the three hydro-economic models developed in this study. As can be seen, from the three hydro-economic model configurations considered in this study, engineering-based and integrated models include a detailed water resources system model. This model is a generic modelling platform that uses a node-link network to simulate the quantitative interactions of features of the water system. The economic-based model, on the other hand, embeds a set of sectoral water supply data as its water component in lieu of the water resources system model. Two economic components are used here, namely an engineering economic impact assessment and an inter-regional supply-side input-output (ISIO) model to examine the usefulness and importance of capturing the interactions of elements of the economic system. The former evaluates only direct impacts on the sector or region where the change is imposed, while the latter evaluates direct and indirect economic impacts by capturing the cross-sectoral and inter-regional connectedness.

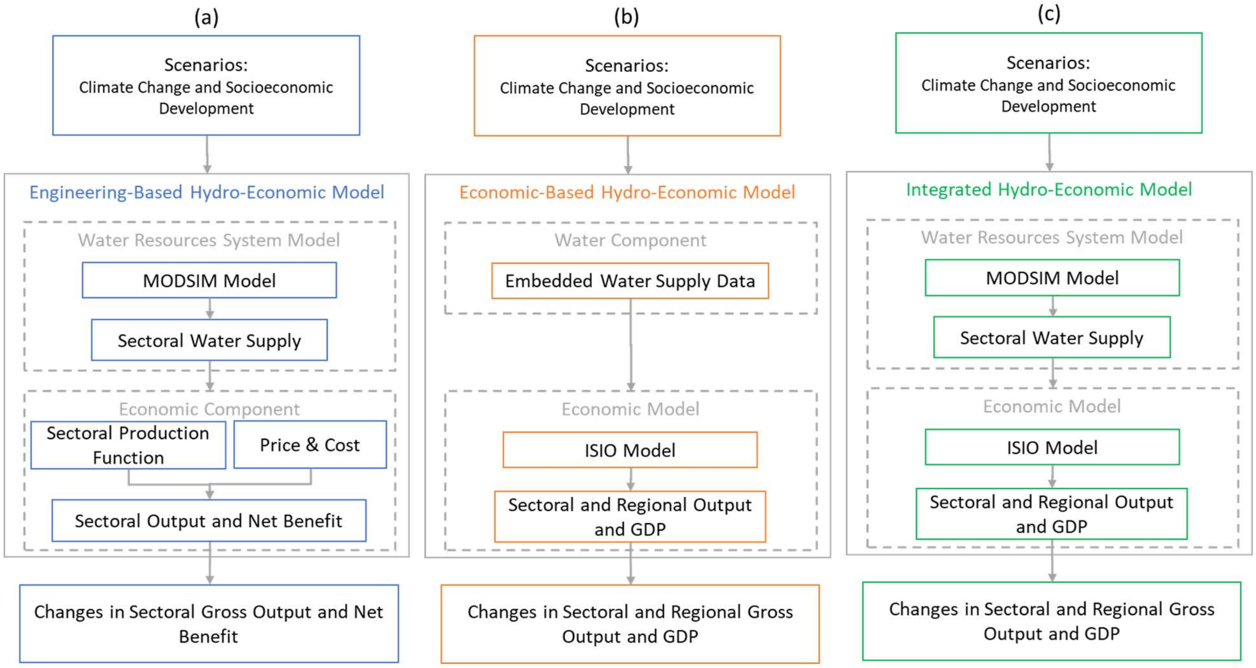


Figure 5.4. The structure and workflow of the three hydro-economic models: (a) engineering, (b) economic, and (c) integrated hydro-economic models

To study the applicability of these three hydro-economic models as decision support tools, we apply them to evaluate the economic response of the SaskRB to a set of scenarios. As can be seen in Figure 5.4, the amount of water supply to various sectors is estimated under different scenarios. This is implemented in the engineering and integrated models by simulating the water resources system under these scenarios and in the economic model by directly changing the water supply dataset without any simulation. For example, under a climate change scenario, if the streamflow decreases by 10%, the sectoral water supply in the economic-based model will change proportionately, unlike the other two models where the changes in the sectoral water supply might be different from the decrease in the streamflow because they will result from simulating the streamflow reduction by the water resources system model. The resulting sectoral water supply is then entered into the economic component, which is a crop yield function for the irrigation sector in the engineering-based model of this study. The model estimates the output of the irrigation sector in the regions where water availability is changed under each scenario. The economic impact assessment is implemented in the economic-based and integrated models through the ISIO model, which accounts for the connectedness among various sectors and regions. Finally, the economic impacts of different scenarios on the SaskRB estimated by the three models are compared at sectoral and regional scales. The scenarios that are considered in this study are described in the next section.

5.4. Scenarios

The three hydro-economic models were applied to evaluate the economic impacts of changes in water availability on the “Irrigated crop and animal production” sector using all the three models and on other sectors where possible due to the structure of the model. These changes were imposed on the SaskRB under two different scenarios, namely climate change and socioeconomic development. While climate change alters the spatial and temporal variability in the quantity of available water, socioeconomic changes affect the quantity of available water by increasing the demand for water in upstream areas. In this chapter, we assume that the climate change scenario only reduces the quantity of water supply, and the socioeconomic scenario only increases the quantity of water demand in the SaskRB. The two scenarios considered in this analysis are elaborated on below.

The first scenario focuses on climate change. Under this scenario, a severe drought event that occurred previously in the SaskRB was selected, and the economic impact of such an event on the river basin should it happen again in the study years was assessed using the three hydro-economic models. 2001 was one of the driest years (also within the 1999-2004 dry period) in the past 100 years in the SaskRB (Wheaton et al., 2005; Bonsal and Regier, 2007; Wittrock and Wheaton, 2007; Marchildon et al., 2008; Corkal et al., 2011). Based on the streamflow data of the South Saskatchewan River at Medicine Hat in Alberta and Saskatoon in Saskatchewan, and of the Saskatchewan River at The Pas in Manitoba, this year is ranked at the 1st percentile in Alberta and the 3rd percentile in Saskatchewan and Manitoba. Comparing the streamflow in 2014 and 2015 with that in 2001 shows that the flow in the latter year 2001 was on average 60% lower than the flow in the former years across the river basin. The difference between the flow of 2001 and the streamflow in the wet year (2014) was higher than in the dry year (2015). This difference also varied across the river basin from upstream Alberta to downstream Manitoba. Nevertheless, we assume this average percentage (i.e., 60%) to uniformly reduce the quantity of the streamflow of the study years (2014 and 2015) and approximate the drought of 2001 while avoiding adding more complexity to the analysis.

The second scenario focuses on socioeconomic development. Under this scenario, an irrigation expansion, which is part of the development plan for Saskatchewan, is considered as the socioeconomic development scenario in this study. Considering this scenario enables us to compare the applicability of the hydro-economic models in evaluating the economic impacts of changes in water availability due to socioeconomic developments concentrated in one part of the river basin on other parts of the basin. This scenario is based on the irrigation expansion plan announced by the Government of Saskatchewan in 2020. Under this scenario, slightly more than 186 thousand hectares are planned to be added to irrigated lands in Saskatchewan receiving water from Lake Diefenbaker in SK-SSRB (Government of Saskatchewan, 2020). It is assumed here that the crops and crop mix of this new development plan are identical to those of the existing irrigation districts in the SK-SSRB region. The water demand for this development was added to the irrigation demand node in the SK-SSRB region in engineering and integrated hydro-economic models. Then, the water resources system model was run, and the impact of having this additional water demand on the sectoral water supply was simulated. The resulting sectoral water supplies were fed into the economic components. In the economic model, on the other hand, the new water demand was added to the irrigation water demand of the SK-SSRB without any changes in the water supply to other sectors (see Section 5.5).

5.5. Modelling Assumptions and Limitations

In simulating the above scenarios by the three hydro-economic models, the following assumptions were made:

- As mentioned earlier, in this study, all analysis is implemented for two years, namely 2014 and 2015. This is because we aimed at investigating the performance of the hydro-economic models for the economic structure of the river basin under different climatic conditions, and the economic data for the three hydro-economic models were available for these years.
- In this study, we investigate the changes in the quantity of available water and assume that the temporal pattern of water availability remains unchanged.
- Under the climate change scenario, a reduction similar to the reduction in water availability is assumed to happen to the irrigation water supply as a sector that is directly affected by changes in water availability in the economic-based hydro-economic model. This is a valid approach in the absence of a water resources system model that simulates the water system, including reservoirs' operational rules, demand priorities, return flows, etc. In engineering-based and integrated hydro-economic models, however, the changes in the water supply to irrigated agriculture were estimated using the water resources system model.
- Under the socioeconomic scenario, the new water demand is added to the irrigation water demand of the SK-SSRB in the economic-based model, and it is assumed that this demand will be fulfilled by the system without any changes in the water supply to other sectors. This is because without the water resources simulation model, it is hard to identify the sectors that will be affected by this extra water demand and assess the extent to which their water supply might be impacted.

In addition to the above mentioned assumptions in simulating the scenarios, the following assumptions and limitations of the modelling exercise here should be kept in mind while interpreting the results. These assumptions and limitations are discussed in different parts of this chapter and consolidated here in this section.

The temporal resolutions of the ISIO and MODSIM models are different. ISIO is based on annual economic data, whereas the MODSIM model for the SaskRB works on a weekly basis. To connect these two models, the time scale for the integrated hydro-economic model is considered to be annual as economic data are not available at finer temporal scales. Therefore, the weekly results of MODSIM are aggregated to the annual level to be used in the integrated model.

The spatial resolutions of the ISIO and MODSIM models are different. IO tables are only available at provincial levels, while MODSIM model is developed for different sub-basins of the SaskRB. Therefore, the spatial study unit for this research was considered a hydro-economic region defined here as parts of the main sub-basins of the SaskRB in each of the three prairie provinces. Since IO tables are not available at the scale of river basins, labor force, population, intra- and inter-regional trade flow data were applied to disaggregate these provincial tables to the level of the hydro-economic regions (Chapter 2). However, different, more or less sophisticated approaches exist in accounting for trade-flows within and between sectors and regions in inter-regional IO models (e.g., Gravity models). A fairly simple approach is used here based on the limited available data and information, namely extracting the inter-regional trade-flows from the domestic trade-flows within and between greater economic regions (Statistics Canada, 2018e) proportionate to the ratio of the labor force and population in each region to the entire province.

In the process of coupling ISIO and MODSIM models, one of the main challenges was deal with different industry classification between the two models and connect the economic sectors in ISIO to demand nodes of MODSIM. Non-irrigation demand nodes in MODSIM were separated proportionate to the ratio of licenses of each sector to the total non-irrigation licenses in each hydro-economic region. This assumption was made in the absence of any reliable data for different sectors aggregated under non-irrigation demand in each sub-basin of the SaskRB. Another important assumption here was to separate hydropower from the "Utilities" sector in IO tables proportionate to the share of hydropower plants in generating electricity in each province (CER, 2020).

5.6. Results

The economic impacts of changes in water availability to the "Irrigated crop and animal production" sector in the SaskRB under climate change and socioeconomic development scenarios are estimated using the three hydro-economic models at sectoral and regional scales. This sector is selected here because of the prominent role of irrigation in the SaskRB, i.e., 75 percent of irrigated agriculture of Canada is in this river basin (Statistics Canada, 2018a). Also, data for the costs and prices related to the production of this sector were available for the study years, namely the years 2014 and 2015. The results are presented for the irrigated crop and animal production sector coming from all models and for the other sectors where they are available due to the structure of the models. The water components of the three hydro-economic models first estimate the changes in the water supply to “Irrigated crop and animal production” under the two scenarios. For example, under the 60% reduction in water availability due to the climate change scenario, irrigation water supply decreased by 18% in 2014 and 45% in 2015 on average across the SaskRB according to the engineering and integrated hydro-economic models, whereas it decreased proportionately to the reduction in water availability in the economic-based model. Then, the economic impacts of these changes in the water supply are estimated by the economic components of the models. These results are presented in the following sub-sections.

5.6.1. Assessing Sectoral Economic Impacts

Figures 5.5 and 5.6 illustrate changes in the sectoral output of the SaskRB estimated by the economic, engineering, and integrated models due to climate change and socioeconomic development scenarios, respectively. The performance of these three hydro-economic models in estimating the economic impacts of the two scenarios at the sectoral level is compared below.

The Engineering-Based Model versus the Integrated Hydro-Economic Model

As can be seen in Figures 5.5 and 5.6, under both scenarios and in both wet and dry years, the engineering-based model overestimates the reduction and increase in the output, respectively, compared with the integrated model estimations. This is possibly related to the fact that, unlike the integrated model, the engineering model does not account for either sectoral or regional interactions. These interactions seem to offset a part of the impacts of changes in the water supply on the output of the water-dependent sectors. For example, under the socio-economic development scenario, the engineering-based model estimates the increase in the output solely in the irrigation sector without accounting for the potential impacts of such a development on other parts of the economy. The integrated model, on the other hand, considers not only the impacts of this scenario on the irrigation sector (directly affected sector), but it also accounts for the indirect impacts of this change on the economy of the SaskRB. As can be seen in Figure 5.6, supplying more water to irrigation comes at the cost of reducing water from hydropower generation and hence a decrease in the output of this sector. Consequently, other sectors, including irrigated agriculture, that purchase the output of hydropower as part of their inputs also suffer from this reduction in the production of hydropower. This yields a lower increase in the output of irrigation using the integrated model than the engineering-based model. Another systematic pattern that can be seen in these results is their magnitude under wet and dry climates. Comparing the changes in the sectoral output of the SaskRB indicates that the economic impacts of water shortage are more pronounced in a dry year (2015) than in a wet year (2014).

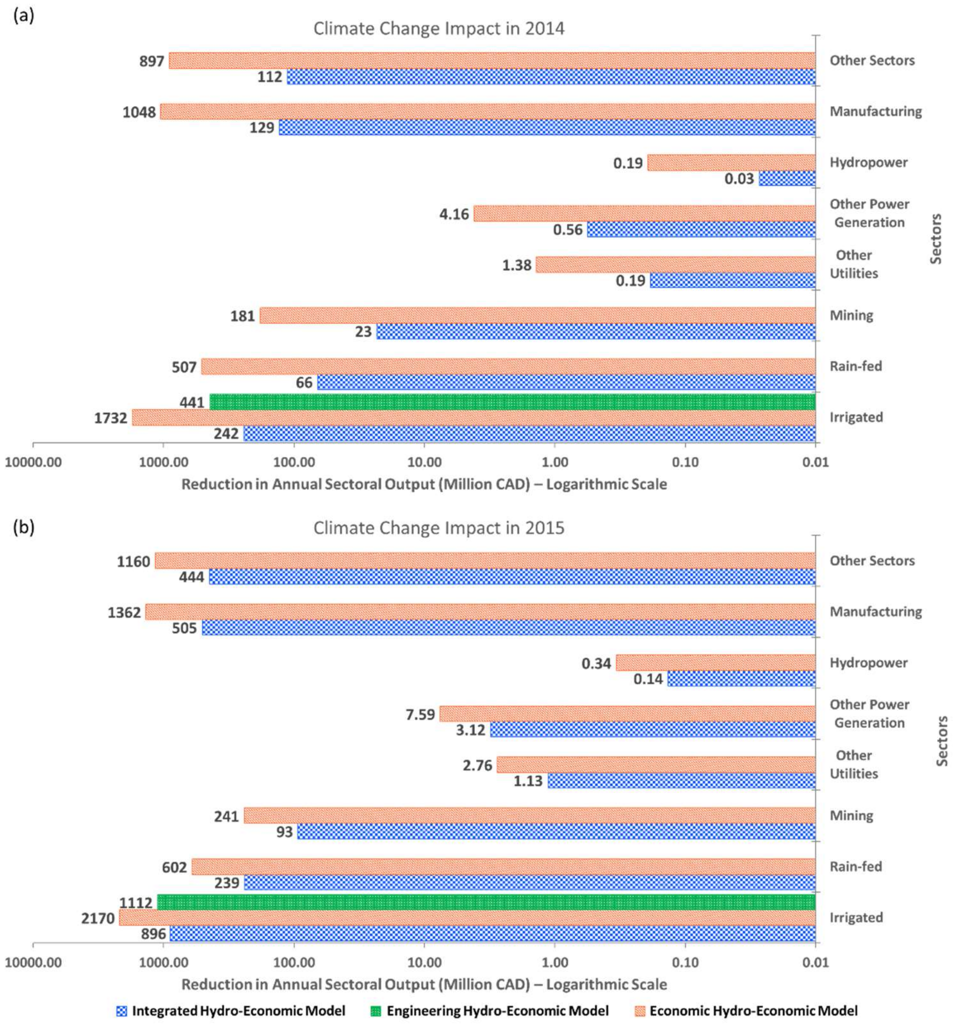


Figure 5.5. Changes in annual sectoral output of the Saskatchewan River Basin due to the climate change scenario in the years (a) 2014 and (b) 2015 using the economic-based, engineering-based, and integrated hydro-economic models (in 2015 prices)

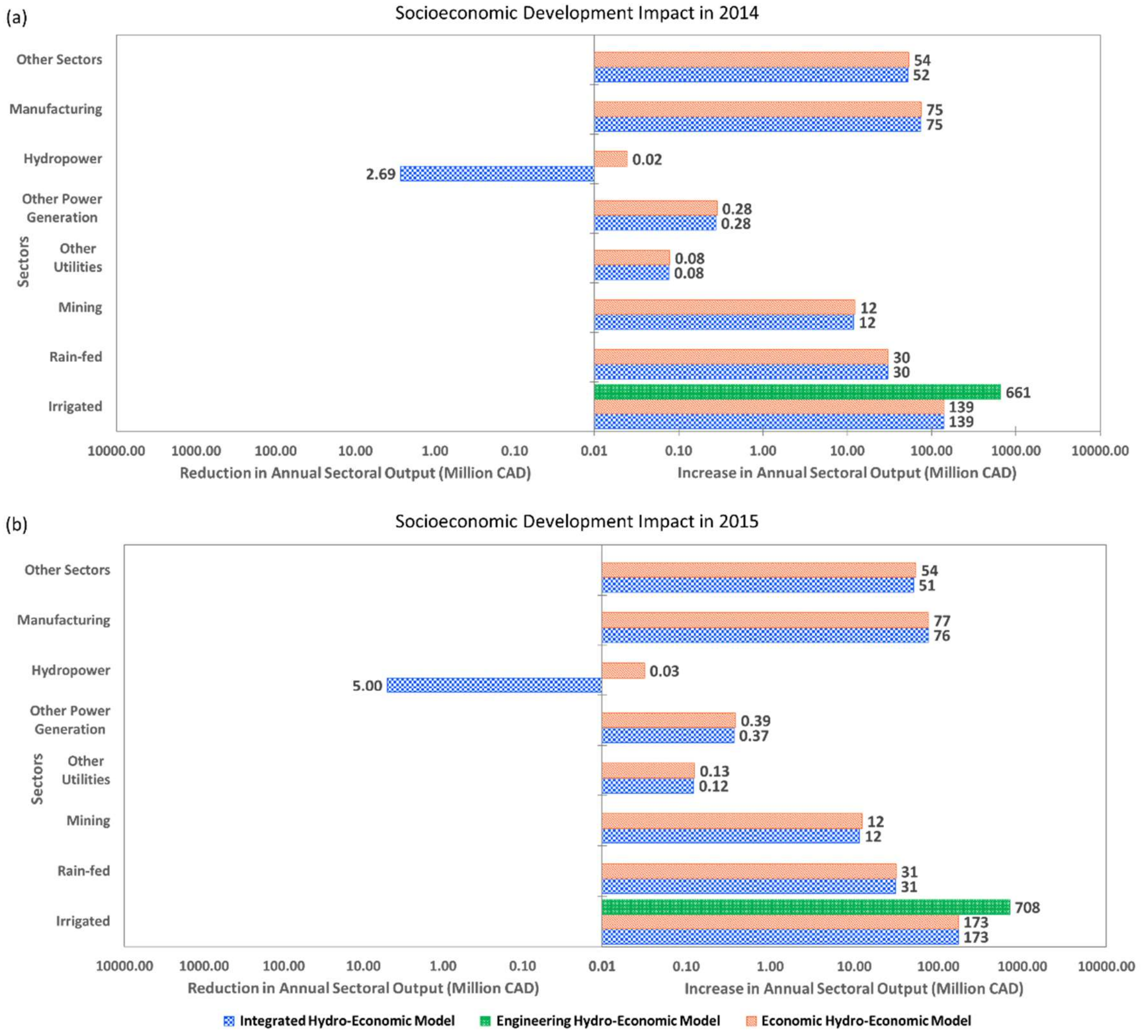


Figure 5.6. Changes in annual sectoral output of the Saskatchewan River Basin due to the socioeconomic development scenario in the years (a) 2014 and (b) 2015 using the economic-based, engineering-based, and integrated hydro-economic models (in 2015 prices). The horizontal axis is on a logarithmic scale.

Interestingly, although the restriction in water supply due to climate change is only imposed on the "Irrigated crop and animal production" sector, the rest of the economy is also impacted. According to Figure 5.5, not only direct water-using sectors but also indirect water-using sectors (i.e., "other sectors") are experiencing reductions in their output due to the climate change scenario. This can be explained by cross-sectoral interactions, which causes the impact of a change imposed on one sector to propagate to the rest of the economy. In the case of this study, the reduction in water supply to the "Irrigated crop and animal production" sector reduces the output of this sector.

Consequently, the purchase of other sectors, such as "Manufacturing" from the output of this sector is affected (reduced here). This change transfers to the rest of the economy through their transactions with either directly affected sectors (i.e., "Irrigated crop and animal production") or indirectly affected ones (e.g., "Manufacturing"). The engineering-based model, however, failed to capture this interconnectedness, and consequently, the indirect impacts are neglected due to the fact that it only accounts for one part of the economy without considering the interconnections with the rest of the economy.

As shown in Figure 5.6, the sectoral output of "Irrigated crop and animal production" under the socioeconomic scenario increases more in the dry year 2015 than in the wet year 2014. This increase can be attributed to the higher crop prices in 2015 for which we accounted, and which lead to a higher amount of monetary output of the irrigation sector in the former year despite the dry climatic conditions. Figure 5.6 also illustrates the tradeoff between "Irrigated crop and animal production" and "Hydropower" sectors. As can be seen, results of the integrated model indicate that allocating more water to expand irrigation in the SK-SSRB causes a reduction in the water supply, and consequently, the output of "Hydropower". This reduction, as expected, is smaller in a wet year due to more water availability. The electricity that other economic sectors, including the irrigation sector, consume in their production process reduces as a result of this change in hydropower's output, which affects the output of these latter sectors.

The Economic-Based Model versus the Integrated Hydro-Economic Model

The first systematic pattern detected in the results generated by the economic-based and integrated models (Figures 5.5 and 5.6) is the overestimation of output changes by the economic model although both models use identical economic components. The difference between the estimations of these two models is much higher under the climate change scenario. As can be seen in Figure 5.5, the highest difference occurs in 2014 in the output estimation for "Irrigated crop and animal production". The economic model estimates a 1,732 million CAD reduction for this sector due to the climate change scenario, while this reduction is 242 million CAD according to the integrated model.

The considerable difference in estimations of the two models can be attributed to the fact that the economic-based model ignores the interactions between the elements of the water resources and demand system. The water resources system model in the integrated model simulates the water system under the climate change scenario and estimates the amount of water supplied to different sectors under the new water availability conditions. For example, under the climate change scenario, in both years 2014 and 2015, water resources simulations indicated that irrigation water demand can be fulfilled in regions with small irrigated areas (and demand), including AB-NSRB, SK-NSRB, and SK-SRB. According to these results, the reduction in the irrigation water supply is limited to AB-SSRB and SK-SSRB, where the majority of irrigated lands are located. However, as the economic model is not informed by the water resources system model, it considers the reduction in water availability to be equally imposed on irrigation sectors in all regions. Moreover, the water resources system model supplies water to different sectors in AB-SSRB and SK-SSRB based on not only the amount of available water but also the priorities of different sectors (water users) and reservoir operational rules. By neglecting these interactions of the elements in the water system, the economic-based model imposes a uniform restriction on irrigation water supply in all regions, which leads to considerably higher reductions in the output of this sector in the SaskRB due to the climate change scenario compared with the integrated model.

According to Figure 5.6, the difference between the economic and integrated models' estimates is small for almost all sectors due to the socioeconomic scenario. The striking difference, in this case, is the inability of the economic model to capture the tradeoffs between different sectors. Under the socioeconomic scenario, irrigation water demand increases in one region (SK-SSRB) due to irrigation expansion. The water resources system model simulates the new conditions and estimates the amount of water that can be supplied to irrigation and other sectors. Since water is limited, increasing water supply in one sector (or region) might cause a reduction in the water supply to other sectors (or regions).

The economic-based model, however, lacks such a mechanism to estimate the amount of water that other sectors should sacrifice to supply water to the new irrigation demand. Under this scenario, supplying water to the new irrigation demand comes at the cost of a reduction in the water supply to hydropower, i.e., 2.7 and 5 million CAD in the years 2014 and 2015, respectively. Since the economic structures of both economic and integrated models are identical, for those sectors that water supply remains unchanged or changes with the same amount under both models, the output estimations are almost the same. However, for those sectors that have higher interactions with hydropower, where water supply remains unchanged under the economic model but decreases under the integrated model, the output estimations of these models differ slightly (Figure 5.6).

5.6.2. Assessing Regional Economic Impacts on the Irrigation Sector

Figure 5.7 shows the spatial distribution of changes in the output of irrigated agriculture in different regions due to the climate change and socioeconomic development scenarios in the years 2014 and 2015 using the economic-based, engineering-based, and integrated hydro-economic models in 2015 prices. The performance of these three hydro-economic models in estimating the economic impacts of the two scenarios on the output of the "Irrigated crop and animal production" sector at the regional level is compared below.

The Engineering-Based Model versus the Integrated Hydro-Economic Model

Not surprisingly, the economic impact of reductions in the water supply to a directly water-dependent sector, such as irrigation, is more pronounced in a dry year than in a wet year. For example, the output reduction of "Irrigated crop and animal production" in AB-SSRB is almost 4 times larger in the dry year 2015, i.e., 842 million CAD than in the wet year 2014, i.e., 198 million CAD due to the climate change scenario.

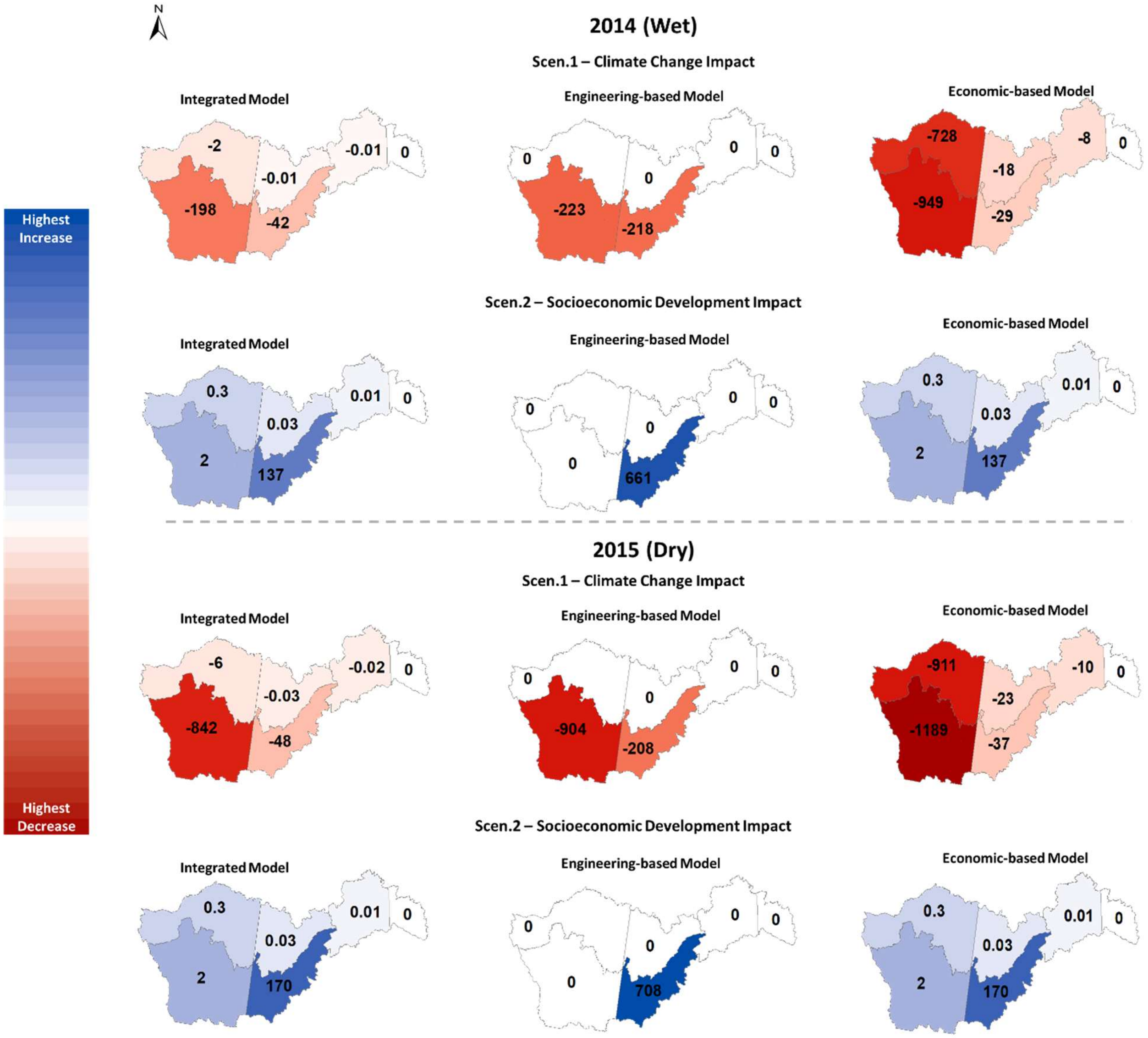


Figure 5.7. Spatial distribution of changes in the annual output of "Irrigated crop and animal production" under different scenarios using the economic-based, engineering-based, and integrated models in the years 2014 and 2015 (Million CAD in 2015 prices)

As can be seen in Figure 5.7, the engineering-based model estimates the economic impacts only in regions where the water supply is changed, while the integrated model estimates these impacts on the output of irrigated agriculture in all regions of the SaskRB. Irrigated lands in the SaskRB are mostly concentrated in AB-SSRB and SK-SSRB, which makes these regions major water users for agriculture. Simulating the two scenarios by the water resources system model shows that although water supply to irrigation in AB-SSRB and SK-SSRB changes under these scenarios, the river system still can supply the limited irrigation demands in the rest of the SaskRB. Hence, the engineering model estimates no changes in the output of irrigation in regions other than AB-SSRB and SK-SSRB. The integrated model, in contrast, estimates the impacts of these scenarios on the output of irrigation in all regions using changes in inter-regional transactions of the irrigation sector in addition to the changes in its water supply. The results of the integrated model, however, indicate that the changes in the output of this sector in the regions other than AB-SSRB and SK-SSRB are relatively small. For instance, under the climate change scenario in the year 2015, the integrated model estimates 842 and 48 million CAD reductions in the output of "Irrigated crop and animal production" in AB-SSRB and SK-SSRB, respectively, whereas the next largest reduction is a 6 million CAD in the output of this sector in AB-NSRB (Figure 5.7).

The Economic-based Model versus the Integrated Hydro-Economic Model

Similar to the pattern seen in the sectoral results (Figure 5.5), under the climate change scenario, reductions in the output of "Irrigated crop and animal production" are considerably overestimated by the economic-based model. As discussed in Section 5.6.1, this is attributed to the fact that the economic model lacks a proper mechanism to simulate the interactions of the elements of the water system. The influence of the water resources system model on the estimated results is more obvious when we compare the results of the two scenarios. Unlike the climate change scenario, under the socioeconomic scenario, the change in the water supply to "Irrigated crop and animal production" is identical in both economic and integrated models (i.e., the amount of water supplied to the new irrigated area is identical in both models). Consequently, the changes in the output of this sector estimated by the economic-based and integrated models are almost the same in all regions of the SaskRB (Figure 5.7). It should be noted that these results only include the changes in the output of the "Irrigated crop and animal production" sector, and hence the impact of tradeoffs between this sector and "Hydropower" are not shown in this figure.

5.6.3. Assessing Economic Impacts on the Entire Economy

By comparing the performance of the three models in estimating the economic impacts of the two scenarios on the output of irrigated crop and animal production, we observed that the most promising results seem to be generated by the integrated model. Therefore, in this section, we present the results of the integrated model to examine the impacts of these scenarios on the entire economy of the SaskRB. This analysis helps better understand the importance of applying a hydro-economic model that accounts for cross-sectoral and inter-regional connectedness over the entire river basin. Although the economic impacts of different scenarios on a particular sector, like irrigation, might be more pronounced in the regions where the main changes to the water supply occur, the impacts on the entire economy in other regions might not be negligible. Figure 5.8 presents the spatial distribution of changes in the gross output of different regions of the SaskRB due to the two scenarios in the years 2014 and 2015.

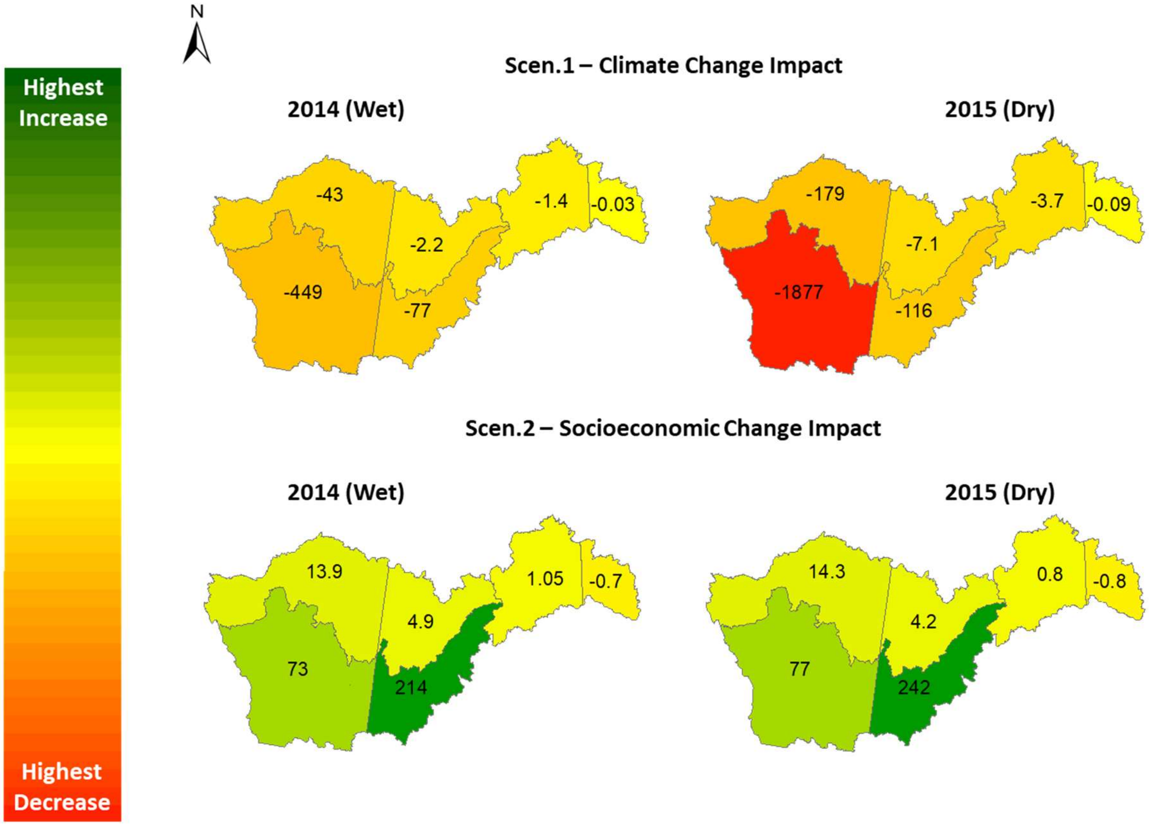


Figure 5.8. Spatial distribution of changes in annual gross output of different regions due to the two scenarios using the integrated hydro-economic model (Million CAD in 2015 prices)

As illustrated in this figure, due to the climate change scenario in both wet and dry years, the highest reduction in the regional output occurs in AB-SSRB. This reduction is 449 and 1,877 million CAD (in 2015 price levels) in the years 2014 and 2015, respectively. Notably, apart from this highly affected region, the economic impacts of this scenario on SK-SSRB and AB-NSRB are not negligible. SK-SSRB loses 77 and 116 million CAD of its gross output in the years 2014 and 2015, respectively, and AB-NSRB experiences reductions of 43 and 179 million CAD in 2014 and 2015, respectively.

Under the socioeconomic scenario, upstream regions benefit from the irrigation expansion in SK-SSRB, whereas downstream regions seem to suffer from this development plan (Figure 5.8). The increase in the output of irrigation agriculture in this region amplifies the production of sectors such as manufacturing (e.g., food processing firms) in other regions, including AB-SSRB and AB-NSRB, which enhances the gross output of these latter regions. On the other hand, as mentioned earlier, the output of the "Hydropower" sector decreases due to the reduction in the water supply to this sector as a tradeoff for water allocation to the irrigation expansion in SK-SSRB. Consequently, the gross output of the downstream regions suffers from this irrigation expansion due to the higher share of the hydropower generation in their economy. This economic loss, however, decreases under the wet climate where more water is available to supply to both irrigation and hydropower sectors (Figure 5.6). According to Figure 5.8, the largest increase in the regional output under the second scenario, after SK-SSRB, occurs in AB-SSRB, i.e., 73 and 77 million CAD in 2014 and 2015, respectively. The next largest increase is around 14 million CAD in AB-NSRB. These results indicate that although the impacts of changes in the water supply to "Irrigated crop and animal production" on the output of this very sector might be negligible in the regions where water supply remains unchanged (Figures 5.7), the impacts on the entire economy of these regions can still be considerable. For example, only accounting for the effects of the socioeconomic scenario on irrigation sector, we observe small benefits to "Irrigated crop and animal production" in Alberta regions, i.e., AB-SSRB and AB-NSRB (Figure 5.7), whereas if we consider the effects of this scenario on the other water-use and non-water-use sectors, the benefits to these regions are considerably higher, i.e., 73 and 77 million CAD in the AB-SSRB in the years 2014 and 2015, respectively (Figure 5.8).

5.7. Discussion and Conclusions

This chapter attempts to examine the applicability of three hydro-economic modelling approaches as decision support tools in a transboundary water management context. As such, engineering-based, economic-based, and integrated hydro-economic models were developed for the transboundary Saskatchewan River Basin (SaskRB) in Canada, and their usefulness was investigated under climate change and socioeconomic development scenarios. The engineering-based model benefits from a relatively straightforward modelling process as the crop yield functions are defined for the irrigation demand nodes in the water resources system model, and hence the economic and water components are compatible. This is, of course, in addition to the efforts required to develop the water resources system model. The development of the economic-based model, on the other hand, is challenging as this model aims at reconciling the economic data released at the administrative scale (provincial) with water supply data collected at the hydrological scale (river basin). The modelling process is even more complicated for the integrated hydro-economic model as the economic model is neither spatially nor temporally compatible with the water resources system model. The different industry classifications between the two models further add to the challenge of coupling the water and economic components of this model.

These models were applied to study the economic impacts of the climate change and socioeconomic development scenarios for two years with different climate conditions (water availability), namely the wet year 2014 and the dry year 2015. Economic impacts of the climate change scenario in these years indicate that, as expected, climate-change-induced economic losses are higher in the dry year than in the wet year. However, under the socioeconomic scenario, although the production of the agriculture sector was lower in physical units in the dry year 2015 than the wet 2014 (Alberta Agriculture and Forestry, 2016), economic benefits of irrigation expansion on “Irrigated crop and animal production” seem to be higher in the dry year. This can be attributed to the higher prices of crops in 2015 (see Section 5.2 and Table 5.1). On the other hand, the decline in the price of oil and potash in late 2014 and 2015 seems to restrain the increase of the gross output in the rest of the economy in 2015 due to irrigation expansion. Although the ISIO model is based on the assumption of fixed prices, our findings indicate that having more than one ISIO model can provide insights about the effects of these changes in prices between years on the economic impacts of exogenous shocks. Furthermore, these changes in the prices in one sector affect the output of that very sector as well as the output of other sectors that purchase the production of the former sector. As such, applying hydro-economic models, such as the engineering-based model here that does not account for transactions among sectors (regions) is less likely to be appropriate in evaluating the economic impacts of changes in water availability.

The climate change scenario here was a rough simulation of the 2001 drought should it happen again in the years 2014 and 2015. Our findings show that under this scenario in the dry year 2015, among the three models, the integrated model estimates the agricultural economic losses (1,135 million CAD) closest to the actual loss of the 2001 drought in the three prairie provinces estimated by Wheaton et al. (2005), which was 933 million CAD. The engineering-based model only accounts for irrigation losses, and yet its estimation of reductions in gross output (1,112 million CAD) is higher than the actual loss of the agriculture sector (irrigation and rain-fed) in 2001. The economic-based model, on the other hand, accounts for both irrigation and rain-fed losses, but it lacks a mechanism to simulate the changes in the water supply to these sectors under the climate change scenario. This model, therefore, estimates the agricultural losses much higher (i.e., 2,772 million CAD) than the actual losses of the 2001 drought event.

Analyzing the performance of the three models in simulating the two scenarios at the sectoral level, we show that the engineering model fails to capture the indirect economic impacts of changes in the water supply. The economic component of this model functions individually for each sector and hence does not capture the inter-sectoral transactions. As a result, the engineering model, unlike the economic and integrated models, is limited to estimating only direct economic impacts without accounting for indirect impacts. The economic model, in contrast, captures both direct and indirect impacts of changes in the water supply on the economy of the SaskRB. This model, however, is incapable of simulating the interactions of different features of the water system under different scenarios, which in this case, leads to considerably high overestimations (Section 5.6.1). Benefitting from both the detailed water resources system model and the ISIO model, the integrated hydro-economic model accounts for the water resources interactions (e.g., demand priorities, regulating infrastructure, return flow, etc.) while capturing the direct and indirect economic impacts of changes in water availability due to different scenarios.

The engineering-based and economic-based models also fail to capture tradeoffs among different sectors, which is crucial in decision-making in multi-sectoral (i.e., multi-stakeholder) water management problems. Water is limited, and hence tradeoffs are inevitable when the amount of available water is restricted or the demand for water increases. One might argue that defining the production function for the "Hydropower" sector in the engineering model enables the analyst to estimate the tradeoffs between irrigation and hydropower. While this is a valid argument, it calls for mindful consideration of the inter-sectoral economic transactions between these sectors (or other conflicting sectors) and the rest of the economy. Questions such as "how much would the production of other sectors be affected due to a reduction in hydropower production?" should be answered. As mentioned earlier, the structure of the engineering model is not designed to address these questions. The economic model, on the other hand, is designed to capture these inter-sectoral transactions and answer such questions. Yet, using this latter model alone, analysts are not capable of identifying tradeoffs unless being informed by a water resources system model about the amount of water that other sectors, such as hydropower, sacrifice to provide water for the new irrigation project. Hence, the integrated model with detailed economic and water resources system components is required to inform decision-makers around both economic and water management aspects of these situations.

Results of our study indicate that the engineering-based model is not an appropriate tool for assessing economic impacts on neither the rest of the economy nor regions other than the ones where the water supply is altered. Water resources system models are developed based on hydrological and hydraulic principles and hence hardly evaluate the impacts of changes in the water availability in one part of the river basin on the upstream regions. These models typically focus on estimating such impacts on downstream regions. By coupling these models with engineering-based economic components that exclude sectoral/regional transactions, the engineering hydro-economic models also fail to capture the economic impacts of changes in one part of the basin on the rest of the economy. Such a model, however, can provide insight into estimating economic impacts in the case of problems focusing on a single sector in a region without accounting for connections with other sectors/regions. We illustrate that the overall impact of these scenarios on different parts of the SaskRB is not always negligible.

According to our results, economic-based models, such as the ISIO model, that capture the sectoral/regional interconnectedness can be included in the hydro-economic framework to provide insights into the economic consequences of changes in the water availability in various sectors and different parts of the river basin. However, the IO-based models, including the ISIO model used in this study, are linear models based on assumptions such as fixed prices for all goods and services in the period of analysis. While more sophisticated economic models, e.g., computable general equilibrium models can be applied to improve the estimations of the economic impacts, the IO-based models can still be helpful due to their relatively simpler development process and application to provide insight into short-term economic impacts and their sectoral/regional distributions.

Our findings revealed that although the economic-based model might estimate the economic impacts of the socioeconomic scenario at the regional level in line with the estimations of the integrated model, it fails to do so for the climate change scenario. The water resources component of the integrated model simulates the scenarios accounting for the priorities of different water demands, operational rules of reservoirs, etc. These configurations of the water system and the interactions among its different elements help the integrated model to simulate possible changes in the water supply to sectors due to different scenarios. Therefore, under scenarios that change the water availability in the river basin, applying the integrated model is required to simulate the water resources system's internal processes in supplying water to various sectors. This is also crucial in identifying tradeoffs among different sectors under new development scenarios, as discussed earlier.

Overall, modelling approaches, such as the engineering-based and economic-based models, with a detailed representation of one system and a simplified representation of the other, can be helpful in dealing with disciplinary problems. However, they do not suffice to support large-scale decision making in multi-sectoral and multi-regional river basins. To inform decision-making about sustainable water (re)allocation among competing uses in a transboundary river basin, an interdisciplinary modelling framework is required that can simulate the water system under plausible future states of the world while capturing the cross-sectoral and inter-regional connectedness in the economic system. This study showed that the integrated hydro-economic model developed by coupling detailed economic and water resources system models can be applied as such a model. Benefiting from capabilities of both water and economic components, this model provides insight into assessing the direct and indirect short-term economic impacts of climate change and socioeconomic development and identifying tradeoffs between competing water-use sectors. This information can support policymakers, particularly in multi-jurisdictional river basins, in preparing sustainable water (re)allocation strategies.

Author Contributions

LE developed the models, wrote the computer codes, designed the numerical experiments, and performed them all. LE contributed to the interpretation of the results and wrote the paper. RB and SR commented on the manuscript and contributed to the editing of the paper.

Chapter 6

Conclusions and Future Research Directions

6.1. Summary

The need for moving towards "Responsible Consumption and Production", the United Nation's Sustainable Development Goal 12 (see Figure 1.1), motivated this Ph.D. research to incorporate economy, as the study of the allocation of scarce resources, into water management. To do so, this dissertation developed an integrated hydro-economic model for a transboundary river basin that can simulate interactions between water and economic systems. The model is developed for a case study of the multi-jurisdictional Saskatchewan River Basin as the first model of this kind developed for the entire river basin. For the first time, the stability of the inter-regional supply-side input-output models was investigated under different climatic conditions and over different years. The integrated model was applied in a novel way to identify sectoral and regional vulnerabilities and inform decision-making about sustainable and robust water allocation strategies in a transboundary river context. The economic impact and vulnerability assessment were conducted here by exploring the distribution of cross-sectoral and inter-regional economic impacts of changes in water allocation strategies. These contributions were achieved in different chapters of this dissertation, as summarized below.

In chapter 2, the inter-regional supply-side input-output (ISIO) model was developed for the transboundary Saskatchewan River Basin (SaskRB) as the first inter-regional hydro-economic model developed for the entire SaskRB. This model includes a set of water intake data for raw water-use sectors. The performance of the model was shown under two hypothetical scenarios where water supply was reduced due to climate change. Under one scenario, no policy interventions were considered, while under the other scenario, policy measures were considered to mitigate the economic impacts of such a reduction in the water supply. Results showed that by considering policy measures, the economic loss of climate-change-induced water shortages could be reduced in the SaskRB. This illustrated the usefulness of applying the ISIO model in providing insight into the expected direct and indirect economic impacts of climate change and policy interventions on water availability at hydrological and administrative scales.

Developing the ISIO models based on the economic data collected for a certain year under particular climatic conditions raises questions about the reliability of these models in evaluating economic impacts for other years under climate conditions different from the model's base year. Chapter 3 addressed this concern by developing ISIO models for four years under different climatic conditions, namely two dry years (2009 and 2015) and two wet years (2013 and 2014), and investigating the reliability of these models in predicting one another's gross output. Findings of this chapter revealed that these models perform well in predicting the output for years with similar climates to the model's base year and when the prediction year and the model's base year are not too far in time from each other.

Informed by the findings of Chapter 3, two ISIO models, namely 2014 (wet) and 2015 (dry) models were selected to be included in the integrated hydro-economic model of the SaskRB in Chapter 4. These models were coupled with a water resources system model developed for this river basin in MODSIM-DSS. This is the first integrated hydro-economic model developed for the SaskRB that encompasses the entire river basin, simulates both water and economic systems and their interactions, and captures direct and indirect economic impacts. As no changes were detected in the pattern of results generated for the years 2014 and 2015, only results for the year 2015 were presented.

The integrated hydro-economic model was applied to assess the sectoral and regional vulnerabilities of the SaskRB to reductions in future water availability, for example due to climate change, and inform decision-making about sustainable and robust water allocation strategies that reduce these vulnerabilities under increasing water scarcity. As such, the sensitivity of the SaskRB's economy to reductions in the water supply to various sectors and regions was assessed, and sectors/regions were ranked based on the influence of reducing their water supply on the economy of the entire river basin. Finally, the response of a water allocation strategy developed based on economic considerations (i.e., minimize economic costs) to changes in water availability was compared with the response of the existing water allocation system in the SaskRB. Findings indicated that the economic loss due to reductions in water availability can be reduced by allocating water among competing uses based on economic considerations assuming that there are no additional costs due to the reallocation of resources.

Chapter 5 explored the advantage of using the integrated hydro-economic model to support decision-making related to climate change and socio-economic development scenarios compared with an economic oriented model (ISIO with water data included) and an engineering model (MODSIM with an economic component estimating the quantity of production multiplied by market prices) developed for the SaskRB. The findings of this chapter revealed that to better understand the relative impact of exogenous shocks on the economy of a multi-sectoral and multi-regional river basin, an integrated hydro-economic model captures both the relevant water resources features as well as the relevant cross-sectoral and inter-regional economic connectedness. Although such an integrated model is data-demanding and challenging to create in terms of coupling the water and economic components with different resolutions, it generates substantially different results than a more engineering or economic oriented approach in a multi-regional and multi-sectoral context. Because of the higher level of detail, this integrated model is considered more reliable in assessing the distribution of both the cross-sectoral and inter-regional impacts of changes in water availability and inform decision-making about sustainable and robust water allocation strategies.

6.2. Limitations and Modelling Assumptions

In developing the integrated hydro-economic model for the Saskatchewan River Basin, several assumptions had to be made. Some of these assumptions are related to the structure of the economic and water resources system models, while others are associated with the available data at different spatial and temporal scales and the integration of the two models. These limitations and assumptions have been discussed in relevant chapters of this dissertation, and in the following, I am consolidating them all under three main groups.

Economic Assumptions

- This study deals with managing limited water resources, while the Leontief Input-Output (IO) model is formulated based on the assumption of an economy with unlimited resources. This model estimates the impacts of changes in final demand on the sectoral production using fixed input coefficients (Leontief, 1936). Therefore, the supply-side IO alternative was applied here. This approach estimates the impacts of changes in primary inputs on sectoral production using fixed output coefficients (Ghosh, 1958). The Leontief production function is a perfect complements production function, where inputs are assumed not to be substitutable due to the fixed proportion of inputs. Therefore, a change in the technical rate of substitution imposes a constant change in the proportion of inputs of the production structure (Miller and Blair, 2009). This seriously undermines the use of, for example, water-saving technologies in the models to improve the water productivity, or the productivity of any other input factor, or the substitution of production factors (e.g., capital with labor). In the supply-side IO model, the model is designed to estimate the impacts of changes in the supply of inputs, while the distribution of outputs in the economy is assumed to be fixed, meaning that a change in a sector's output (as a result of altering its input) imposes a proportionate change in the sales from that sector to the rest of the economy (Davis and Salkin, 1984; Miller and Blair, 2009). In reality, supply and demand are expected to change over time as a result of scarcity and, consequently, the prices of input and output factors. IO models are unable to cope with or account for these market mechanisms to predict new equilibria under changing conditions. The results presented here, therefore reflect expected short-term impacts with no technological adaptations to the new conditions, and hence merely give a snapshot of how the economic output and valued added would change if the imposed water availability restrictions would occur overnight.

- IO models, either conventional or supply-side, are based on a linear model structure. This has implications for evaluating the economic impacts of large-scale exogenous changes. The economic system might react differently (in a non-linear way) to high perturbations, for example, due to changes in water supply, resulting in disproportionate non-linear economic impacts. Therefore, in assessing the sensitivity of the economy to changes in the water supply to different sectors and regions – with a relatively small marginal change (e.g., 1%) in the water supply – the model might be considered to provide reliable results as in Chapter 4. In this case, the sensitivity of the economy to relatively small changes in sectoral/regional water supply is assessed which are not expected to generate large and possibly non-linear responses. This may change if we try to account for larger exogenous shocks. For example, a computable general equilibrium (CGE) model developed for the Canadian economy at national level showed that a 25% reduction in water intake due to introducing new water prices caused a maximum of 1.4% GDP loss at the sectoral level (Rivers and Groves, 2013). This non-proportionate response to reductions in the amount of water intake has resulted from the structure of the CGE models that, unlike the IO-based models, allows for demand and supply to change and achieve a new equilibrium under the new situation. This leads us to conclude that the IO-based models are mainly helpful in providing insights in the order of magnitude of the direct and indirect instantaneous (short-term) effects of an exogenous intervention (policy or otherwise, e.g., climate), and the associated relative importance of regional/sectoral connectivity and hence the distribution of the economic impacts of exogenous shocks. These models, however, are not expected to be very reliable for making longer term predictions or predicting market-clearing behavior of sectors (industry) and actors (government, households) where demand and supply move towards an equilibrium based on the commodities' price signals.

- Prices of the goods and services are assumed to remain constant in the IO-based models. This assumption might be violated in reality, particularly between the base year of the model and the time for which the model is applied to estimate the economic impacts. This assumption and the static nature of these models (the next assumption) make the IO models less appropriate for informing longer term forecasts. They give at most an indication of the expected short-term direct and indirect impacts of, for example, a policy intervention if that intervention would take place in a year with similar conditions to the specific year for which the IO model is built.
- The IO models capture the structure of an economy at a certain point in time. These models are developed based on IO tables for a specific year without accounting for endogenous technological innovation and change, which may change the structure of economies (Leontief et al., 1953; Leistritz and Murdock, 1981; Miller and Blair, 2009). This puts a big question mark on the reliability of these models in predicting the economic impacts for other years. The present research tries to address this question by developing models for four years and testing their reliability in replicating each other's output in Chapter 3. Not only changes in the economic structure from one year to another affect the performance of these models, but also

varying water availabilities due to climatic conditions between the model's base year and the year for which the economic impacts are predicted may influence the results. The results of this study suggest that these different climatic conditions may influence predicted output under varying climatic conditions and hence, if possible, a sensitivity analysis should be conducted to evaluate the economic impacts under different climate conditions using models based on years reflecting the range of climatic conditions for which they were built.

- There are no additional costs in reallocating resources to generate gross output under the imposed water supply restrictions, labor is, for example, assumed to be completely mobile between different economic sectors. This is typically referred to as transaction costs in economics (Williamson, 1994).

Water Resources Assumptions

- In testing the reliability of ISIO models under different climatic conditions, two "wet" and two "dry" years were selected (Chapter 3). These years were selected based on two considerations: first, not being an extremely wet/dry year, and secondly, availability of the economic and water intake data. The two relatively dry years are 2009 and 2015. Based on the annual flow levels of the South Saskatchewan River at Medicine Hat in Alberta and Saskatoon in Saskatchewan, and of the Saskatchewan River at The Pas in Manitoba, the year 2009 is ranked at the 13th, 11th, and 14th percentile in Alberta, Saskatchewan, and Manitoba, respectively, and 2015 is ranked at the 20th percentile in Alberta and Saskatchewan and 34th percentile in Manitoba. The relatively wet years were 2013 and 2014. According to the same streamflow data for these years, the year 2013 is ranked at the 75th, 80th, and 84th percentile in Alberta, Saskatchewan, and Manitoba, respectively, and 2014 is ranked at the 80th percentile in Alberta and 88th percentile in Saskatchewan and Manitoba. I avoided considering extremely wet/dry years here because under extreme climate conditions, exceptional water management strategies different from regular strategies in the river basin might be adopted, whereas this research was aimed at testing the reliability of the ISIO models under relatively more frequent climate conditions. However, the average annual flow is less likely to be appropriate to give a complete picture of the water availability in a certain year as the amount of precipitation might be lower than average in some months (e.g., cropping season) and higher than average in others. This is crucial, particularly for sectors, such as agriculture, for which both the timing and amount of water availability are important. Therefore, summer precipitation is considered here in addition to the annual streamflow to address this issue.

- In the early stages of this study, the ISIO model in chapters 2 and 3 was not coupled yet with the water resources system model (MODSIM), and hence the water intake data were extracted from data published by Statistics Canada (2018). This water intake dataset is bi-annual and only available at the national level. Assumptions, therefore, had to be made in extracting regional water intake data from this national dataset in the absence of other data as described in Chapter 2. These assumptions, such as extracting sectoral water intake proportionate to the sectoral GDP in provinces, extracting water intake in sub-basins according to the ratio of national water intake in sub-basins in each province, interpolating the water intake data of the years 2013 and 2015 to estimate water intake for 2014, etc. were relaxed when the ISIO model was coupled with the MODSIM model for the SaskRB in Chapters 4 and 5.

Integration Assumptions

- The spatial resolutions of the ISIO and MODSIM models are different. IO tables are only available at provincial levels, while MODSIM model is developed for different sub-basins of the SaskRB. Therefore, the spatial study unit for this research was considered a hydro-economic region defined here as parts of the main sub-basins of the SaskRB in each of the three prairie provinces. Since IO tables are not available at the scale of river basins, labor force, population, intra- and inter-regional trade flow data were applied to disaggregate these provincial tables to the level of the hydro-economic regions (Chapter 2). However, different, more or less sophisticated approaches exist in accounting for trade-flows within and between sectors and regions in inter-regional IO models (e.g., Gravity models). I used a fairly simple approach here based on the limited available data and information, namely extracting the inter-regional trade-flows from the domestic trade-flows within and between greater economic regions (Statistics Canada, 2018e) proportionate to the ratio of the labor force and population in each region to the entire province. The findings of Chapter 3 suggest that the assumptions in the process of downscaling do not seem to affect the performance of the models at the scale of the entire river basin, but prediction errors increase substantially at spatially disaggregated levels.

- In the process of coupling ISIO and MODSIM models, one of the main challenges was to connect the economic sectors in ISIO to demand nodes of MODSIM (Chapters 4 and 5). Non-irrigation demand nodes in MODSIM were separated proportionate to the ratio of licenses of each sector to the total non-irrigation licenses in each hydro-economic region. This assumption was made in the absence of any reliable data for different sectors aggregated under non-irrigation demand in each sub-basin of the SaskRB.

- To make the industry classification of the ISIO and MODSIM models compatible, another important assumption was to separate hydropower from the "Utilities" sector in IO tables proportionate to the share of hydropower plants in generating electricity in each province (CER, 2020).

- The temporal resolutions of the ISIO and MODSIM models are different. ISIO is based on annual economic data, whereas the MODSIM model for the SaskRB works on a weekly basis. To connect these two models, the time scale for the integrated hydro-economic model is considered to be annual as economic data are not available at finer temporal scales. Therefore, the weekly results of MODSIM are aggregated to the annual level to be used in the integrated model.

6.3. Future Research Directions

The following issues were not included in the present dissertation but may be included in future research informed by this work.

- Considering feedback loops from economy to the water resources system. The economic and water resources system components of the integrated hydro-economic model in this dissertation were coupled with a one-way connection, meaning that the impacts of water supply restrictions were evaluated in economic terms, and not the changes in economic production and consumption again on the water system. However, to assess the impacts of economic changes on the water system as well, feedback loops may be considered in the future.

- Including a hydrological model in the integrated hydro-economic model to simulate the hydrological processes, such as rainfall-runoff, infiltration, etc. in the river basin. The integrated hydro-economic model does not include a hydrological component. Therefore, the changes in river flow or other features of the model under scenarios such as climate change had to be estimated exogenously and entered into the model therefore also exogenously. Adding a hydrological model to the integrated model can facilitate and improve the performance of this model in simulating different scenarios.
- Conducting a sensitivity analysis to see the relative influence of different technical coefficients on the performance of the model. The performance of the models developed for different years under different climatic conditions was compared here already, showing that technical coefficients change over time, as expected. It would also be interesting and relevant to investigate the sensitivity of the models' output to changes in different technical coefficients. Alternatively, a completely new general equilibrium economic model would have to be created that includes more flexibility to account for possible substitution possibilities, for example between water sources and introducing water saving technologies instead of reducing the production of water use sectors.
- Considering tradeoffs among different sectors (regions) under the economically optimal allocation strategy. In Chapter 4, the economically optimal water allocation strategy was designed based on minimizing the economic loss of the entire SaskRB. However, it would be interesting and insightful to consider a multi-objective optimization to minimize sectoral/regional loss but also other additional criteria such as food and energy security, instead of this single objective optimization problem to identify sectoral/regional tradeoffs under the economically optimal allocation.
- Identifying tradeoffs between environmental and economic objectives. The present dissertation was focused on evaluating the economic impacts of changes in water availability due to policy interventions or other drivers like climate change. However, the impacts of allocating water for economic objectives on the amount and timing of the

environmental flow should be evaluated as well. This may be included in future work and lead to identifying tradeoffs between environmental and economic objectives.

- Including a water quality component in the model. As water quality is one of the main water management challenges in the SaskRB (e.g., Wheater and Gober, 2013), it would be interesting to couple a water quality model with the integrated hydro-economic model of the SaskRB. This can help to understand the interactions between the economy and water system not only from the quantitative perspective but also from the qualitative viewpoint.
- The water resources system model here excludes other sources of water, such as groundwater, poorer quality water, or water reuse due to the lack of reliable data. As some sectors, such as manufacturing in the prairie provinces, use other sources of water in addition to surface freshwater (Statistics Canada, 2020a and 2020b), it would be interesting to account for these sources in the integrated hydro-economic model as well.
- Water trading in water markets among different water users in the SaskRB, as a climate change adaptation measure (e.g., Levin-Koopman et al., 2017), is not considered in this study. However, from the three provinces sharing the SaskRB, Alberta is the only province that allows license trading among the license holders (Halliday and Associates, 2009). For example, during the drought of 2001, farmers in some irrigation districts in the South Saskatchewan River Basin in Alberta temporarily traded their water entitlement (Nicole and Klein, 2006). It would be insightful to consider water markets in future hydro-economic studies of the SaskRB.

6.4. Concluding Remarks

The overarching objective of this dissertation was to develop an integrated hydro-economic model for a transboundary river basin to inform sustainable and robust water management. By achieving this objective, the present dissertation aimed at answering seven research questions. In the first step in Chapter 2, an inter-regional supply-side input-output (ISIO) model that includes sectoral water intake was developed for the transboundary Saskatchewan River Basin (SaskRB) to understand the relationship between sectoral water intake and sectoral production in this river basin (research question 1). The results of this step showed that the economic loss of the river basin under reductions in water supply due to climate change could be substantially reduced (up to 50%) by considering relevant policy measures (research question 2).

Next, testing the temporal reliability of the ISIO models under different climatic conditions and over several years in Chapter 3 showed that these models perform well in predicting the economic impacts for years with climatic conditions similar to the model's base year and over a short period of time. However, prediction errors can be considerably high at sectoral and spatially disaggregated levels, particularly over longer temporal gaps (research question 3). It was concluded from this step that to evaluate the economic impacts for years under different climate conditions, more than one ISIO model developed for different climatic conditions should be considered.

To answer the next research question (research question 4) and identify the most vulnerable sectors and regions to changes in water supply, the integrated hydro-economic model was created and applied to conduct the sensitivity analysis as described in Chapter 4. The resulted distribution of cross-sectoral and inter-regional impacts provides insight into identifying sectors and regions where reducing water supply is most influential on the economy of the SaskRB. The findings of this chapter also indicated that a water allocation strategy based on these economic considerations can reduce the economic loss of water restrictions (between 28 to 79%) compared to the existing priority-based water allocation system.

Finally, the usefulness of cross-sectoral and inter-regional connectedness in evaluating the economic impacts in a transboundary river context was investigated in Chapter 5 (research question 5). This step illustrated that in a multi-sectoral and multi-regional river basin, ignoring either interactions among different elements of the water resources and demand system or interconnections among various economic sectors/regions deteriorates the performance of a hydro-economic model in evaluating the economic impacts. Results showed up to 3 orders of magnitude overestimations in the outputs from modelling approaches other than the integrated approach, which justifies the application of the integrated hydro-economic model despite its data-demanding nature and challenging development process (research question 6).

Overall, the research conducted here attempts to inform decision-making about the economic consequences of different water (re)allocation strategies and other drivers, including climate change and socio-economic development. Despite its limitations (Section 6.2), the integrated hydro-economic model that is developed in this dissertation provides insight into estimating the short-term direct and indirect economic impacts of exogenous shocks on the transboundary SaskRB. The findings of this research also advance our understanding of the relative importance of economic impacts on various economic sectors and different regions.

6.5. Challenges

This dissertation is the outcome of interdisciplinary research, which attempts to bring together water management and economy and inform decision-makers about sustainable and robust water allocation strategies. This was a challenging process from both a technical and non-technical perspective. Despite this challenging process, findings of this research reveal that the synergy between different disciplines leads to achieving a more reliable and multi-dimensional understanding of the consequences of various water allocation strategies under climate change and socio-economic developments, as described in Chapter 5. The technical and non-technical challenges are briefly mentioned in this section.

Technical Challenges

The main technical challenges of this research include (1) finding reliable data at scales relevant to water resources management from both hydrological and economic points of view and (2) coupling the water resources system model and the economic model with different temporal and spatial resolutions and incompatible industry classifications.

Other Challenges

One of the most non-technical challenging steps in this process was dealing with different terminologies used in two different disciplines, i.e., water resources management and engineering, and economics. This became even more challenging for terms with well-established but different definitions and applications in both disciplines, such as efficiency, vulnerability, and robustness. Therefore, finding common grounds to connect these disciplines and to communicate the findings with policymakers and a broader range of audiences can be considered as the backbone of such interdisciplinary attempts.

6.6. Stakeholders’ Engagement

This study has considered stakeholders’ engagement in its process from the early stages. To date, several interactions have been made with representatives from Agriculture and Agri-Food Canada, the Saskatchewan Ministry of Agriculture, the Ministry of Agriculture and Forestry in Alberta, the Saskatchewan Water Security Agency, Alberta Environment and Parks, the Saskatchewan Chamber of Commerce (the Water Council), and SaskPower. The following objectives are followed through these transactions.

- To access reliable data and information (where possible).
- To have Stakeholders’ opinion on the assumptions that have been made in the absence of reliable data (e.g., water licenses, actual water use, industry classifications, sectoral production, etc.).
- To involve stakeholders in the process of scenario development (in collaboration with the Integrated Modelling Program for Canada (IMPC) water policy team).
- To design the study in a way that corresponds to stakeholders’ needs.
- To help decision-makers with more efficient water management and planning decisions (e.g., informing Alberta and Saskatchewan water authorities on the economic consequences of different water management strategies).

The following presentations have been given (in addition to the presentations at IMPC annual meetings) to inform stakeholders of the structure and preliminary results of this study.

- Developing a Hydro-economic Model for the Saskatchewan River Basin. (2019). **Oral Presentation** at the Water Council of the Saskatchewan Chamber of Commerce. Regina, Saskatchewan, Canada.
- The Economic Response of the Saskatchewan River Basin to Water Supply Restrictions due to Climate and Policy Change. (2019). **Poster Presentation** at the Ag-Research Expo (GWF) at University of Saskatchewan, Saskatchewan, Canada.
- The Hydro-economic Model for the Saskatchewan River Basin. (2019). **Oral presentation** at a meeting with SaskPower, Saskatchewan, Canada.

References

Ahrends, H., Mast, M., Rodgers, C., & Kunstmann, H. (2008). Coupled hydrological–economic modelling for optimised irrigated cultivation in a semi-arid catchment of West Africa. Environmental Modelling & Software, 23(4), 385-395.

Alberta Agriculture and Forestry. (2019). Daily Crop Evapotranspiration. Irrigation Management Branch, Alberta Agriculture and Rural Development.

Alberta Agriculture and Forestry. (2016). Agriculture Statistics Yearbook 2015. ISBN 978-1-4601-2978-4. Retrieved from https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd16172/$FILE/2015_ag_yearbook.pdf.

Alberta Environment and Parks (AEP). (2018). Water Licenses Data in Alberta. Personal Communications, May 2018.

Alberta Environment and Parks. (2002). Water Resources Management Model (WRMM) Computer Program Description. Alberta, Canada.

Ali, M. K., & Klein, K. K. (2014). Implications of current and alternative water allocation policies in the Bow River Sub Basin of Southern Alberta. Agricultural water management, 133, 1-11.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO Irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations, 56(97), e156.

Almazán-Gómez, M. A., Duarte, R., Langarita, R., & Sánchez-Chóliz, J. (2019). Effects of water re-allocation in the Ebro river basin: A multiregional input-output and geographical analysis. Journal of environmental management, 241, 645-657.

Amjath-Babua, T.S., Sharmab, B., Brouwer, R., Rasulb, G., Wahide, S.M., Neupaneb, N., Bhattaraif, U. and Sieber, S. (2019). Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Applied Energy, 239: 494-503. https://doi.org/10.1016/j.apenergy.2019.01.147

Antonelli, M., Roson, R., & Sartori, M. (2012). Systemic input-output computation of green and blue virtual water 'flows' with an illustration for the Mediterranean region. Water Resources Management, 26(14), 4133-4146. https://doi.org/10.1007/s11269-012-0135-9

Arjoon, D., Mohamed, Y., Goor, Q., & Tilmant, A. (2014). Hydro-economic risk assessment in the eastern Nile River basin. Water Resources and Economics, 8, 16-31.

Asadzadeh, M., Razavi, S., Tolson, B. A., & Fay, D. (2014). Pre-emption strategies for efficient multi-objective optimization: Application to the development of Lake Superior regulation plan. Environmental Modelling and Software, 54, 128–141. https://doi.org/10.1016/j.envsoft.2014.01.005

ASCE Task Committee on Sustainability Criteria. (1998). Sustainability Criteria for Water Resources Systems. ASCE, Reston, Virginia, USA.

Badham, J., Elsawah, S., Guillaume, J. H., Hamilton, S. H., Hunt, R. J., Jakeman, A. J., ... & Bammer, G. (2019). Effective modeling for Integrated Water Resource Management: A guide to contextual practices by phases and steps and future opportunities. Environmental Modelling & Software, 116, 40-56. https://doi.org/10.1016/j.envsoft.2019.02.013

Basheer, M., Wheeler, K. G., Ribbe, L., Majdalawi, M., Abdo, G., & Zagona, E. A. (2018). Quantifying and evaluating the impacts of cooperation in transboundary river basins on the Water-Energy-Food nexus: The Blue Nile Basin. Science of the Total Environment, 630, 1309-1323. https://doi.org/10.1016/j.scitotenv.2018.02.249

Bekchanov, M., Ringler, C., Bhaduri, A., & Jeuland, M. (2016). Optimizing irrigation efficiency improvements in the Aral Sea Basin. Water Resources and Economics, 13, 30–45. https://doi.org/10.1016/j.wre.2015.08.003

Ben-Gal, A., Weikard, H. P., Shah, S. H. H., & van der Zee, S. E. (2013). A coupled agronomic-economic model to consider allocation of brackish irrigation water. Water resources research, 49(5), 2861-2871.

Berrittella, M., Hoekstra, A. Y., Rehdanz, K., Roson, R., & Tol, R. S. (2007). The economic impact of restricted water supply: A computable general equilibrium analysis. Water research, 41(8), 1799-1813.

Beyers, W. B. (1972). On the stability of regional interindustry models: the Washington data for 1963 and 1967. Journal of Regional Science, 12(3), 363-374. doi:10.1111/j.1467-9787.1972.tb00358.x

Bezdek, R. H., & Dunham, C. R. (1978). Structural Change in the American Economy, by Functional Industry Group. Review of Income and Wealth, 24(1), 93-104.

Bhave, A. G., Conway, D., Dessai, S., & Stainforth, D. A. (2016). Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world. Climate Risk Management, 14, 1-10. https://doi.org/10.1016/j.crm.2016.09.004

Bielsa, J., & Duarte, R. (2001). An economic model for water allocation in North Eastern Spain. International Journal of Water Resources Development, 17(3), 397–408. https://doi.org/10.1080/07900620120065165

Blanco-Gutiérrez, I., Varela-Ortega, C., & Purkey, D. R. (2013). Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. Journal of Environmental Management, 128, 144–160. https://doi.org/10.1016/j.jenvman.2013.04.037

Bogra, S., Bakshi, B. R., & Mathur, R. (2016). A Water-Withdrawal Input-Output Model of the Indian Economy. Environmental Science and Technology, 50(3), 1313–1321. https://doi.org/10.1021/acs.est.5b03492

Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., & Sabater, S. (2014). Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Science of the Total Environment, 470, 567-577. https://doi.org/10.1016/j.scitotenv.2013.10.003

Bon, R., & Bing, X. (1993). Comparative stability analysis of demand-side and supply-side input–output models in the UK. Applied Economics, 25(1), 75-79.

Bon, R. (1986). Comparative stability analysis of demand-side and supply-side input-output models. International Journal of Forecasting, 2(2), 231-235.

Bonsal, B., & Regier, M. (2007). Historical comparison of the 2001/2002 drought in the Canadian Prairies. Climate Research, 33(3), 229-242. doi:10.3354/cr033229

Booker, J. F., Michelsen, A. M., & Ward, F. A. (2005). Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin. Water Resources Research, 41(2), 1–15. https://doi.org/10.1029/2004WR003486

Brooymans, H. (2011). Water in Canada: A Resource in Crisis. Canadian Currents.

Brouwer, R., & Hofkes, M. (2008). Integrated hydro-economic modelling : Approaches, key issues and future research directions. Ecological Economics, 66(1), 16-22. https://doi.org/10.1016/j.ecolecon.2008.02.009

Brouwer, R., Hofkes, M., & Linderhof, V. (2008). General equilibrium modelling of the direct and indirect economic impacts of water quality improvements in the Netherlands at national and river basin scale. Ecological Economics, 66(1), 127–140. https://doi.org/10.1016/j.ecolecon.2007.11.015

Brouwer, R., Schenau, S., & Veeren, R. Van Der. (2005). Integrated river basin accounting in the Netherlands and the European Water Framework Directive. Statistical Journal of the United Nations Economic Commission for Europe, 22(2), 111–131.

Brown, J. R. (2017). Irrigation Development as an Instrument for Economic Growth in Saskatchewan: An Economic Impact Analysis (Master's thesis, University of Saskatchewan, Saskatoon, Canada). Retrieved from http://hdl.handle.net/10388/8145.

Bryant, B. P., & Lempert, R. J. (2010). Thinking inside the box: a participatory, computer-assisted approach to scenario discovery. Technological Forecasting and Social Change, 77(1), 34-49. https://doi.org/10.1016/j.techfore.2009.08.002

Cai, X. (2008). Implementation of holistic water resources-economic optimization models for river basin management - Reflective experiences. Environmental Modeling & Software, 23(1), 2–18. https://doi.org/10.1016/j.envsoft.2007.03.005

Cai, X., & Wang, D. (2006). Calibrating holistic water resources–economic models. Journal of Water Resources Planning and Management, 132(6), 414-423.

Cai, X., & Rosegrant, M. W. (2004). Optional water development strategies for the Yellow River Basin: Balancing agricultural and ecological water demands. Water Resources Research, 40(8). https://doi.org/10.1029/2003WR002488

Cai, X., McKinney, D. C., & Lasdon, L. S. (2003). Integrated Hydrologic-Agronomic-Economic Model for River Basin Management. Journal of Water Resources Planning and Management, 129(1), 4–17. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:1(4)

Calzadilla, A., Rehdanz, K., & Tol, R. S. J. (2010). The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. Journal of Hydrology, 384(3–4), 292–305. https://doi.org/10.1016/j.jhydrol.2009.12.012

Canada Energy Regulator (CER). (2020). Canada's Energy Future 2019 dataset. https://www.cerrec.gc.ca/nrg/ntgrtd/ftr/2019/index-eng.html. Accessed May 2020.

Carter, A.P. (1970). Structural Change in the American Economy. Harvard University Press. Cambridge, Massachusette.

Cazcarro, I., Duarte, R., Sánchez Chóliz, J., & Sarasa, C. (2020). Water and production reallocation in the Spanish agri-food system. Economic Systems Research, 32(2), 278-299. https://doi.org/10.1080/09535314.2019.1693982

Cazcarro, I., Duarte, R., & Sánchez Chóliz, J. (2013). Multiregional input-output model for the evaluation of Spanish water flows. Environmental Science and Technology, 47(21), 12275–12283. https://doi.org/10.1021/es4019964

Corkal, D. R., Diaz, H., & Sauchyn, D. (2011). Changing roles in Canadian water management: a case study of agriculture and water in Canada's South Saskatchewan River Basin. International Journal of Water Resources Development, 27(4), 647-664. https://doi.org/10.1080/07900627.2011.621103

Croke, B. F. W., Ticehurst, J. L., Letcher, R. A., Norton, J. P., Newham, L. T. H., & Jakeman, A. J. (2007). Integrated assessment of water resources: Australian experiences. Water Resources Management, 21(1), 351-373. https://doi.org/10.1007/s11269-006-9057-8

Cutlac, I. M., & Horbulyk, T. M. (2011). Optimal water allocation under short-run water scarcity in the South Saskatchewan River Basin. Journal of water resources planning and management, 137(1), 92-100.

Dai, T., & Labadie, J. W. (2001). River basin network model for integrated water quantity/quality management. Journal of water resources planning and management, 127(5), 295-305. https://doi.org/10.1061/(ASCE)0733-9496(2001)127:5(295)

Dalcin, A. P., & Fernandes Marques, G. (2020). Integrating water management instruments to reconcile a hydro-economic water allocation strategy with other water preferences. Water Resources Research, 56(5), e2019WR025558. https://doi.org/10.1029/2019WR025558

Daron, J. (2015). Challenges in using a Robust Decision Making approach to guide climate change adaptation in South Africa. Climatic Change, 132(3), 459-473. https://doi.org/10.1007/s10584-014-1242-9

Davis, H. C., & Salkin, E. L. (1984). Alternative approaches to the estimation of economic impacts resulting from supply constraints. The Annals of Regional Science, 18(2), 25-34. https://doi.org/10.1007/BF01287372

Dellink, R., Brouwer, R., Linderhof, V. & Stone, K. (2011). Bio-economic modelling of water quality improvements using a dynamic Applied General Equilibrium approach. Ecological Economics, 71: 63-79. https://doi.org/10.1016/j.ecolecon.2011.06.001

De Mesnard, L. (2002). Forecast output coincidence and biproportion: two criteria to determine the orientation of an economy. Comparison for France (1980–1997). Applied Economics, 34(16), 2085-2091.

Dessai, S., Hulme, M., Lempert, R., & Pielke Jr, R. (2009). Do we need better predictions to adapt to a changing climate? Eos, Transactions American Geophysical Union, 90(13), 111-112. https://doi.org/10.1029/2009EO130003

Dietzenbacher, E., & Hoen, A. R. (2006). Coefficient stability and predictability in input-output models: a comparative analysis for the Netherlands. Construction Management and Economics, 24(7), 671-680.

Do, P., Tian, F., Zhu, T., Zohidov, B., Ni, G., Lu, H., & Liu, H. (2020). Exploring synergies in the water-food-energy nexus by using an integrated hydro-economic optimization model for the Lancang-Mekong River basin. Science of The Total Environment, 728, 137996. https://doi.org/10.1016/j.scitotenv.2020.137996

Doorenbos, J & Kassam, A.H. (1979) Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. FAO-Food and Agriculture Organization of the United Nations. Rome, Italy.

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., & Howitt, R. E. (2003). Economic-engineering optimization for California water management. Journal of water resources planning and management, 129(3), 155-164.

Drexhage, J., & Murphy, D. (2010). Sustainable Development: From Brundtland to Rio 2012. United Nations. https://doi.org/10.1007/s13398-014-0173-7.2

Droogers, P., & Allen, R. G. (2002). Estimating reference evapotranspiration under inaccurate data conditions. Irrigation and drainage systems, 16(1), 33-45. https://doi.org/10.1023/A:1015508322413

Duarte, R., Sanchez-Choliz, J., & Bielsa, J. (2002). Water use in the Spanish economy : an input-output approach. Ecological Economics, 43(1), 71–85. https://doi.org/10.1016/S0921-8009(02)00183-0

Duarte Pac, R., & Sanchez-Choliz, J. (1998). Analysis of water pollution with input-output models. Transactions on Ecology and the Environment, 23, 311-329. DOI:10.2495/ASE980291

Emami, F., & Koch, M. (2018). Agricultural water productivity-based hydro-economic modeling for optimal crop pattern and water resources planning in the Zarrine River Basin, Iran, in the wake of climate change. Sustainability, 10(11), 3953. https://doi.org/10.3390/su10113953

Escriva-Bou, A., Pulido-Velazquez, M., & Pulido-Velazquez, D. (2017). Economic value of climate change adaptation strategies for water management in Spain's Jucar basin. Journal of Water Resources Planning and Management, 143(5), 04017005. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000735

Esteve, P., Varela-Ortega, C., Blanco-Gutiérrez, I., & Downing, T. E. (2015). A hydro-economic model for the assessment of climate change impacts and adaptation in irrigated agriculture. Ecological Economics, 120, 49–58. https://doi.org/10.1016/j.ecolecon.2015.09.017

Ewing, B. R., Hawkins, T. R., Wiedmann, T. O., Galli, A., Ercin, A. E., Weinzettel, J., & Steen-olsen, K. (2012). Integrating ecological and water footprint accounting in a multi-regional input – output framework. Ecological Indicators, 23, 1–8. https://doi.org/10.1016/j.ecolind.2012.02.025

FAO. (2012). Crop Yield Response to Water. FAO Irrigation and Drainage Paper 66. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/i2800e/i2800e.pdf

Fereidoon, M., & Koch, M. (2018). SWAT-MODSIM-PSO optimization of multi-crop planning in the Karkheh River Basin, Iran, under the impacts of climate change. Science of the Total Environment, 630, 502-516. https://doi.org/10.1016/j.scitotenv.2018.02.234

Fortin, V., Roy, G., Stadnyk, T., Koenig, K., Gasset, N. & Mahidjiba, A. (2018). Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review. Atmosphere-Ocean, 56(3), 178-196. https://doi.org/10.1080/07055900.2018.1474728

Fortin, V., Roy, G., Donaldson, N. & Mahidjiba, A. (2015). Assimilation of radar quantitative precipitation estimations in the Canadian Precipitation Analysis (CaPA). Journal of Hydrology, 531, 296-307. https://doi.org/10.1016/j.jhydrol.2015.08.003

Foster, T., Brozović, N., & Butler, A. P. (2017). Effects of initial aquifer conditions on economic benefits from groundwater conservation. Water Resources Research, 53(1), 744-762.

García, G. A., García, P. E., Rovere, S. L., Bert, F. E., Schmidt, F., Menéndez, Á. N., ... & Podestá, G. P. (2019). A linked modelling framework to explore interactions among climate, soil water, and land use decisions in the Argentine Pampas. Environmental Modelling & Software, 111, 459-471. https://doi.org/10.1016/j.envsoft.2018.10.013

Garcia-Hernandez, J. A., & Brouwer, R. (2020). A multiregional input–output optimization model to assess impacts of water supply disruptions under climate change on the Great Lakes economy. Economic Systems Research, 1-27. https://doi.org/1080/09535314.2020.1805414

Geressu, R. T., & Harou, J. J. (2019). Reservoir system expansion scheduling under conflicting interests. Environmental Modelling & Software, 118, 201-210. https://doi.org/10.1016/j.envsoft.2019.04.002

Ghosh, A. (1958). Input-output Approach in an Allocation System. Economia, 25(97), 58-64.

Gillig, D., McCarl, B. A., & Boadu, F. O. (2001). An economic, hydrologic, and environmental assessment of water management alternative plans for the south central Texas region. Journal of Agricultural and Applied Economics, 33(1379-2016-113215), 59-78. 10.22004/ag.econ.15296

Global Water Partnership Central and Easter Europe (GWP CEE). (2015). Guidelines for the preparation of Drought Management Plans. Development and implementation in the context of the EU Water Framework Directive.

Gómez, C. M., Tirado, D., & Rey-Maquieira, J. (2004). Water exchanges versus water works: Insights from a computable general equilibrium model for the Balearic Islands. Water Resources Research, 40(10). https://doi.org/10.1029/2004WR003235

González, J. F. (2011). Assessing the Macroeconomic Impact of Water Supply Restrictions Through an Input – Output Analysis. Water Resources Management, 25(9), 2335–2347. https://doi.org/10.1007/s11269-011-9811-4

Government of Alberta. (2017). Weekly Economic Review 2015. Retrieved from https://open.alberta.ca/publications/weekly-economic-review-2015#summary.

Government of Alberta. (2016). Highlights of the Alberta Economy 2016. Alberta Economic Development and Trade. Retrieved from https://open.alberta.ca/dataset/10989a51-f3c2-4dcb-ac0f-f07ad88f9b3b/resource/e68b9292-51d5-40e8-8151-d148bda6d473/download/2016-highlights-alberta-economy-2016-07.pdf.

Government of Alberta. (2015). 2015 Cropping Alternatives. Alberta Agriculture and Rural Development. Retived from https://www.alberta.ca/agriprofits-field-crops.aspx

Government of Alberta. (2014). 2014 Cropping Alternatives. Alberta Agriculture and Rural Development. Retived from https://www.alberta.ca/agriprofits-field-crops.aspx

Government of Alberta, Environment. (2010). South Saskatchewan Regional Plan, Water Quantity and Quality Modelling Results. ISBN: 978-0-7785-9004-0.

Government of Saskatchewan. (2020). Saskatchewan Announces $4 Billion Irrigation Project At Lake Diefenbaker. Retrived from https://www.saskatchewan.ca/government/news-and-media/2020/july/02/irrigation-project

Government of Saskatchewan. (2018). The Water Security Agency Act (W-8.1). The Queen's Printer, Regina, Saskatchewan.Retrieved from http://www.publications.gov.sk.ca/freelaw/documents/English/Statutes/Statutes/W8-1.pdf.

Government of Saskatchewan. (2016). Economic Review 2015. Saskatchewan Bureau of Statistics, Report Number 69. Saskatchewan, Canada. Retrieved from https://pubsaskdev.blob.core.windows.net/pubsask-prod/99995/99995-ER2015.pdf.

Graveline, N., Majone, B., van Duinen, R., & Ansink, E. (2014). Hydro-economic modeling of water scarcity under global change: An application to the Gállego river basin (Spain). Regional Environmental Change, 14(1), 119–132. https://doi.org/10.1007/s10113-013-0472-0

Guan, D., & Hubacek, K. (2008). A new and integrated hydro-economic accounting and analytical framework for water resources: A case study for North China. Journal of Environmental Management, 88(4), 1300–1313. https://doi.org/10.1016/j.jenvman.2007.07.010

Haasnoot, M., & Middelkoop, H. (2012). A history of futures: a review of scenario use in water policy studies in the Netherlands. Environmental science & policy, 19, 108-120. https://doi.org/10.1016/j.envsci.2012.03.002

Halliday, R. and Associates. (2009). From the Mountains to the Sea: The State of the Saskatchewan River Basin. Prepared for the Partners FOR the Saskatchewan River Basin.

Harou, J. J., Medellín-Azuara, J., Zhu, T., Tanaka, S. K., Lund, J. R., Stine, S., Oliveres, M. A., & Jenkins, M. W. (2010). Economic consequences of optimized water management for a prolonged, severe drought in California. Water Resources Research, 46(5). https://doi.org/10.1029/2008WR007681

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., & Howitt, R. E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. Journal of Hydrology, 375(3–4), 627–643. https://doi.org/10.1016/j.jhydrol.2009.06.037

Hassanzadeh, E., Elshorbagy, A., Wheater, H., Gober, P., & Nazemi, A. (2016). Integrating supply uncertainties from stochastic modeling into integrated water resource management: Case study of the Saskatchewan River basin. Journal of water resources Planning and Management, 142(2), 05015006.

Hassanzadeh, E., Elshorbagy, A., Wheater, H., & Gober, P. (2014). Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada. Environmental Modelling & Software, 58, 12-26.

Häggmark Svensson, T., & Elofsson, K. (2019). The ex-post cost-effectiveness of nitrogen load reductions from nine countries to the Baltic sea between 1996 and 2010. Water Resources Research, 55(6), 5119-5134. doi:10.1029/2018WR023978

He, L., Horbulyk, T. M., Ali, M. K., Le Roy, D. G., & Klein, K. K. (2012). Proportional water sharing vs. seniority-based allocation in the Bow River basin of Southern Alberta. Agricultural Water Management, 104, 21-31.

Heinz, I., Pulido-Velazquez, M., Lund, J. R., & Andreu, J. (2007). Hydro-economic modeling in river basin management: implications and applications for the European water framework directive. Water resources management, 21(7), 1103-1125. https://doi.org/10.1007/s11269-006-9101-8

Herman, J. D., Reed, P. M., Zeff, H. B., & Characklis, G. W. (2015). How should robustness be defined for water systems planning under change? Journal of Water Resources Planning and Management, 141(10), 04015012. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000509

Herman, J. D., Zeff, H. B., Reed, P. M., & Characklis, G. W. (2014). Beyond optimality: Multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty. Water Resources Research, 50(10), 7692-7713. https://doi.org/10.1002/2014WR015338

Hurd, B. H., & Coonrod, J. (2012). Hydro-economic consequences of climate change in the upper Rio Grande. Climate Research, 53(2), 103-118. DOI: https://doi.org/10.3354/cr01092

Intergovernmental Panel on Climate Change (IPCC). 2020. https://www.ipcc-data.org/guidelines/pages/glossary/glossary_s.html

Irrigation Crop Diversification Corporation (ICDC). (2015). Irrigation Economics and Agronomics. http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2014/11/2015-Economics-Agronomics.pdf

Irrigation Crop Diversification Corporation (ICDC). (2014). Irrigation Economics and Agronomics. http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2014/10/2014_Agronomics_and_Economics.pdf

Jalilov, S. M., Amer, S. A., & Ward, F. A. (2018). Managing the water-energy-food nexus: Opportunities in Central Asia. Journal of hydrology, 557, 407-425.

Jenkins, M. W., Lund, J. R., Howitt, R. E., Draper, A. J., Msangi, S. M., Tanaka, S. K., … Marques, G. F. (2004). Optimization of California's Water Supply System: Results and Insights. Journal of Water Resources Planning and Management, 130(4), 271–280. https://doi.org/10.1061/(ASCE)0733-9496(2004)130:4(271)

Jódar, L., & Merello, P. (2010). Positive solutions of discrete dynamic Leontief input–output model with possibly singular capital matrix. Mathematical and computer modelling, 52(7-8), 1081-1087.

Johnson, T. G. (1986). A dynamic input-output model for small regions. Review of Regional Studies, 16(1), 14-23.

Johnson, T. (1985). A continuous Leontief dynamic input-output model. In Papers of the Regional Science Association, 56(1), 177-188. Springer-Verlag.

Jonkman, S. N., Bočkarjova, M., Kok, M., & Bernardini, P. (2008). Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. Ecological economics, 66(1), 77-90.

Juana, J. S., Mangadi, K. T., & Strzepek, K. M. (2012). The socio-economic impacts of climate change on water resources in South Africa. Water international, 37(3), 265-278. https://doi.org/10.1080/02508060.2012.687505

Kahil, M. T., Ward, F. A., Albiac, J., Eggleston, J., & Sanz, D. (2016). Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management. Journal of Hydrology, 539, 510-524.

Kahil, M. T., Dinar, A., & Albiac, J. (2015). Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. Journal of Hydrology, 522, 95-109. https://doi.org/10.1016/j.jhydrol.2014.12.042

Kahsay, T. N., Arjoon, D., Kuik, O., Brouwer, R., Tilmant, A., & van der Zaag, P. (2019). A hybrid partial and general equilibrium modeling approach to assess the hydro-economic impacts of large dams–The case of the Grand Ethiopian Renaissance Dam in the Eastern Nile River basin. Environmental Modelling & Software, 117, 76-88. https://doi.org/10.1016/j.envsoft.2019.03.007

Kahsay, T. N., Kuik, O., Brouwer, R., & Van Der Zaag, P. (2017). The Economy-Wide Impacts of Climate Change and Irrigation Development in the Nile Basin: a Computable General Equilibrium Approach. Climate Change Economics, 08(01), 1750004. https://doi.org/10.1142/S201000781750004X

Kim, D., & Kaluarachchi, J. J. (2016). A risk-based hydro-economic analysis for land and water management in water deficit and salinity affected farming regions. Agricultural Water Management, 166, 111–122. https://doi.org/10.1016/j.agwat.2015.12.019

Knowling, M. J., White, J. T., McDonald, G. W., Kim, J. H., Moore, C. R., & Hemmings, B. (2020). Disentangling environmental and economic contributions to hydro-economic model output uncertainty: An example in the context of land-use change impact assessment. Environmental Modelling & Software, 127, 104653. https://doi.org/10.1016/j.envsoft.2020.104653

Kulshreshtha, S., & Grant, C. (2003). Economic impact assessment of irrigation development and related activities in Manitoba. Canadian Water Resources Journal, 28(1), 53–67. https://doi.org/10.4296/cwrj2801053

Kwakkel, J. H., & Haasnoot, M. (2019). Supporting DMDU: a taxonomy of approaches and tools. In Decision Making under Deep Uncertainty (pp. 355-374). Springer, Cham.

Kwakkel, J. H., & Jaxa-Rozen, M. (2016). Improving scenario discovery for handling heterogeneous uncertainties and multinomial classified outcomes. Environmental Modelling & Software, 79, 311-321.

Leistritz, F. L., & Murdock, S. H. (1981). The Socioeconomic Impact of Resource Development: Methods for Assessment. Westview Press, Inc.

Lempert, R. J., (2019). Robust Decision Making (RDM). In Decision Making under Deep Uncertainty (pp. 23-51). Springer, Cham. https://doi.org/10.1007/978-3-030-05252-2_2

Lempert, R. J., & Groves, D. G. (2010). Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. Technological Forecasting and Social Change, 77(6), 960-974. https://doi.org/10.1016/j.techfore.2010.04.007

Lempert, R., Nakicenovic, N., Sarewitz, D., & Schlesinger, M. (2004). Characterizing climate-change uncertainties for decision-makers. An editorial essay. Climatic Change, 65(1), 1-9.

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). Shaping the next one hundred years: new methods for quantitative, long-term policy analysis. Rand Corporation.

Lenzen, M. (2009). Understanding virtual water flows: A multiregion input-output case study of Victoria. Water Resources Research, 45(9). doi:10.1029/2008WR007649

Leontief, W. (1970). Environmental Repercussions and the Economic Structure : An Input-Output Approach. The Review of Economics and Statistics, 52(3), 262-271.

Leontief, W. (1970). The Dynamic Inverse. In W. Leontief (Ed.), Input-Output Economics (pp. 294-320). (1986). New York, Oxford, Oxford University Press.

Leontief, W., Chenery, H. B., Clark, P. G., Duesenberry, J. S., Ferguson, A. R., Grosse, A. P., Grosse, R. N., Holzman, M., Isard, W., & Kistin, H. (1953). Studies in the Structure of the American Economy. Theoretical and Empirical Explorations in Input-Output Analysis. Oxford University Press.

Leontief, W. (Ed.). (1951). The Structure of American Economy, 1919-1939. An Emperical Apprication of Equilibrium Analysis. Oxford University Press.

Leontief, W. (1941). The Structure of American Economy, 1919-1929. An Emperical Apprication of Equilibrium Analysis. Harvard University Press.

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. The Review of Economics and Statistics, 18(3), 105–125.

Levin-Koopman, J., Kuik, O., Tol, R. & Brouwer, R. (2017). The potential of water markets to allocate water between industry, agriculture, and public water utilities as an adaptation mechanism to climate change. Mitigation and Adaptation Strategies for Global Change, 22(2): 325. doi:10.1007/s11027-015-9662-z

Levin-Koopman, J. F., Kuik, O., Tol, R. S., & Brouwer, R. (2015). Water scarcity from climate change and adaptation response in an international river basin context. Climate Change Economics, 6(01), 1550004

Li, X., Zhang, C., & Huo, Z. (2020). Optimizing irrigation and drainage by considering agricultural hydrological process in arid farmland with shallow groundwater. Journal of Hydrology, 124785.

Liew, C. J. (2000). The dynamic variable input-output model: An advancement from the Leontief dynamic input-output model. The Annals of Regional Science, 34(4), 591-614.

Liu, Y., Wang, R., Guo, T., Engel, B. A., Flanagan, D. C., Lee, J. G., ... & Wallace, C. W. (2019). Evaluating efficiencies and cost-effectiveness of best management practices in improving agricultural water quality using integrated SWAT and cost evaluation tool. Journal of Hydrology, 577, 123965. https://doi.org/10.1016/j.jhydrol.2019.123965

Llop, M. (2013). Water reallocation in the input–output model. Ecological Economics, 86, 21-27. https://doi.org/10.1016/j.ecolecon.2012.10.020

López-Morales, C. A., & Duchin, F. (2015). Economic Implications of Policy Restrictions on Water Withdrawals From Surface and Underground Sources. Economic Systems Research, 27(2), 154–171. https://doi.org/10.1080/09535314.2014.980224

López-Morales, C., & Duchin, F. (2011). Policies and technologies for a sustainable use of water in Mexico: A scenario analysis. Economic Systems Research, 23(4), 387-407. https://doi.org/10.1080/09535314.2011.635138

Loucks, D. P. & Van Beek, E. (2017). Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Springer.

Loucks, Daniel P. & Van Beek, E. (2005). Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications. Paris: UNESCO.

Luckmann, J., Grethe, H., McDonald, S., Orlov, A., & Siddig, K. (2014). An integrated economic model of multiple types and uses of water. Water Resources Research, 50(5), 3875-3892. https://doi.org/10.1002/2013WR014750

Lund, J. R. (2015). Integrating social and physical sciences in water management. Water Resources Research, 51(8), 5905-5918. https://doi.org/10.1002/2015WR017125

Lund, J. R., Cai, X., & Characklis, G. W. (2006). Economic engineering of environmental and water resource systems. Journal of Water Resources Planning and Management, ASCE, Vol. 132 (6). https://doi.org/10.1061/(ASCE)0733-9496(2006)132:6(399)

Lutter, S., P, S., Giljum, S., Wieland, H., & Mutel, C. (2016). Spatially explicit assessment of water embodied in European trade : A product-level multi-regional input-output analysis. Global Environmental Change, 38, 171–182. https://doi.org/10.1016/j.gloenvcha.2016.03.001

MacEwan, D., Cayar, M., Taghavi, A., Mitchell, D., Hatchett, S., & Howitt, R. (2017). Hydroeconomic modeling of sustainable groundwater management. Water Resources Research, 53(3), 2384-2403. https://doi.org/10.1002/2016WR019639

Mahfouf, J.-F., Brasnett, B., & Gagnon, S. (2007). A Canadian Precipitation Analysis (CaPA) project: Description and preliminary results. Atmosphere-Ocean, 45(1), 1–17. https://doi.org/10.3137/ao.v450101

Maier, H. R., Guillaume, J. H., van Delden, H., Riddell, G. A., Haasnoot, M., & Kwakkel, J. H. (2016). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? Environmental Modelling & Software, 81, 154-164. https://doi.org/10.1016/j.envsoft.2016.03.014

Malek, K., Adam, J., Stockle, C., Brady, M., & Rajagopalan, K. (2018). When Should Irrigators Invest in More Water-Efficient Technologies as an Adaptation to Climate Change? Water Resources Research, 54(11), 8999-9032.

Maneta, M. P., Cobourn, K., Kimball, J. S., He, M., Silverman, N. L., Chaffin, B. C., Ewing, S., & Maxwell, B. (2020). A satellite-driven hydro-economic model to support agricultural water resources management. Environmental Modelling & Software, 134, 104836. https://doi.org/10.1016/j.envsoft.2020.104836

Marchildon, G. P., Kulshreshtha, S., Wheaton, E., & Sauchyn, D. (2008). Drought and institutional adaptation in the Great Plains of Alberta and Saskatchewan, 1914–1939. Natural Hazards, 45(3), 391-411. DOI 10.1007/s11069-007-9175-5

Martz, L.W., Bruneau, J. F., & Rolfe, J. T. (Eds.). (2007). Climate Change and Water: SSRB Final Technical Report. Climate Change Impact and Adaptation Program, Natural Resources Canada. Ottawa, Ontario, Canada.

McCarl, B. A., Musumba, M., Smith, J. B., Kirshen, P., Jones, R., El-Ganzori, A., ... & Hynninen, R. (2015). Climate change vulnerability and adaptation strategies in Egypt's agricultural sector. Mitigation and adaptation strategies for global change, 20(7), 1097-1109. https://doi.org/10.1007/s11027-013-9520-9

Medellín-Azuara, J., Lund, J. R., & Howitt, R. E. (2007). Water Supply Analysis for Restoring the Colorado River Delta, Mexico. Journal of Water Resources Planning and Management, 133(5), 462–471.

https://doi.org/10.1061/(ASCE)0733-9496(2007)133:5(462)

Meng, Y., Liu, J., Leduc, S., Mesfun, S., Kraxner, F., Mao, G., ... & Wang, Z. (2020). Hydropower production benefits more from 1.5° C than 2° C climate scenario. Water Resources Research.

Midmore, P. (1993). Input-Output Forecasting of Regional Agricultural Policy Impacts. Journal of Agricultural Economics, 44(2), 284-300.

Miller, R. E., & Blair, P. D. (Eds.). (2009). Input-Output Analysis: Foundations and Extensions (2nd ed.). Cambridge University Press.

Mirchi, A., Watkins, D. W., Engel, V., Sukop, M. C., Czajkowski, J., Bhat, M., Rehage, J., Letson, D., Takatsuka, Y., & Weisskoff, R. (2018). A hydro-economic model of South Florida water resources system. Science of the Total Environment, 628, 1531-1541. https://doi.org/10.1016/j.scitotenv.2018.02.111

Morway, E. D., Niswonger, R. G., & Triana, E. (2016). Toward improved simulation of river operations through integration with a hydrologic model. Environmental Modelling & Software, 82, 255-274. https://doi.org/10.1016/j.envsoft.2016.04.018

New, M., & Hulme, M. (2000). Representing uncertainty in climate change scenarios: a Monte-Carlo approach. Integrated assessment, 1(3), 203-213. https://doi.org/10.1023/A:1019144202120

Ng, T. L., Eheart, J. W., Cai, X., & Braden, J. B. (2011). An agent-based model of farmer decision-making and water quality impacts at the watershed scale under markets for carbon allowances and a second-generation biofuel crop. Water Resources Research, 47(9).

Nguyen, D. C. H., Maier, H. R., Dandy, G. C., & Ascough II, J. C. (2016). Framework for computationally efficient optimal crop and water allocation using ant colony optimization. Environmental Modelling & Software, 76, 37-53. https://doi.org/10.1016/j.envsoft.2015.11.003

Nicol, L. A., & Klein, K. K. (2006). Water market characteristics: Results from a survey of southern Alberta irrigators. Canadian Water Resources Journal, 31(2), 91-104. https://doi.org/10.4296/cwrj3102091

North Saskatchewan Watershed Alliance. (2008). Assessment of Climate Change Effects on Water Yield from the North Saskatchewan River Basin. Retrieved from https://www.nswa.ab.ca/resource/assessment-of-climate-change-effects-on-water-yield-from-the-north-sask-river-basin/

Okuyama, Y., Sonis, M., & Hewings, G. J. (2006). Typology of structural change in a regional economy: a temporal inverse analysis. Economic Systems Research, 18(2), 133-153.

Paterson Earth & Water Consulting. (2015). Economic Value of Irrigation in Alberta. Prepared for the Alberta Irrigation Projects Association. Lethbridge, Alberta, Canada.

Payet-Burin, R., Kromann, M., Pereira-Cardenal, S., Strzepek, K. M., & Bauer-Gottwein, P. (2019). WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water–energy–food–climate nexus. Hydrology and Earth System Sciences, 23(10), 4129-4152. https://doi.org/10.5194/hess-23-4129-2019

Pérez-Blanco, C. D., Essenfelder, A. H., & Gutiérrez-Martín, C. (2020). A tale of two rivers: Integrated hydro-economic modeling for the evaluation of trading opportunities and return flow externalities in inter-basin agricultural water markets. Journal of Hydrology, 584, 124676. https://doi.org/10.1016/j.jhydrol.2020.124676

Pérez Blanco, C. D., & Thaler, T. (2014). An input-output assessment of water productivity in the castile and León region (Spain). Water (Switzerland), 6(4), 929–944. https://doi.org/10.3390/w6040929

Polenske, K. R. (1970). An empirical test of interregional input-output models: Estimation of 1963 Japanese production. The American Economic Review, 60(2), 76-82.

Pomeroy, J. W., Fang, X., & Williams, B. (2009). Impacts of Climate Change on Saskatchewan's Water Resources. Centre for Hydrology, University of Saskatchewan, 6, 1–46.

Prairie Provinces Water Board. (1969). Master Agreement on Apportionment. Retrieved from https://www.ppwb.ca/uploads/media/5cad077eeae53/master-agreement.pdf?v1.

Raa, T. T. (1986). Dynamic input-output analysis with distributed activities. The Review of Economics and Statistics, 300-310.

Rayner, S. (2000). Prediction and other approaches to climate change policy. Prediction: Science, Decision Making, and the Future of Nature. Island Press, Covelo, CA, 269-296.

Razavi, S., Asadzadeh, M., Tolson, B., Fay, D., Moin, S., Bruxer, J., & Fan, Y. (2013). Evaluation of new control structures for regulating the Great Lakes System: Multiscenario, multireservoir optimization approach, Journal of Water Resources Planning and Management, 140(8), 1–14. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000375.

Renzetti, S., & Dupont, D. P. (2017). Water Policy and Governance in Canada (Vol. 17). https://doi.org/10.1007/978-3-319-42806-2

Ridoutt, B. G., Hadjikakou, M., Nolan, M., & Bryan, B. A. (2018). From Water-Use to Water-Scarcity Footprinting in Environmentally Extended Input–Output Analysis. Environmental Science and Technology, 52(12), 6761-6770. https://doi.org/10.1021/acs.est.8b00416

Ritschard, G. (1983). Computable qualitative comparative static techniques. Econometrica: Journal of the Econometric Society, 1145-1168. https://doi.org/10.2307/1912056

Rivers, N., & Groves, S. (2013). The welfare impact of self-supplied water pricing in Canada: a computable general equilibrium assessment. Environmental and Resource Economics, 55(3), 419-445. DOI 10.1007/s10640-013-9633-3

Russell, R.R. & Wilkinson, M. (1979). Microeconomics: A Synthesis of Modern and Neoclassical Theory. New York. John Wiley and Sons.

Saskatchewan Water Security Agency (SWSA). (2018). Water Licenses Data in Saskatchewan. Personal Communications.

Saskatchewan Water Security Agency (SWSA). (2012). 25 year Saskatchewan water security plan action. Retrieved from https://www.wsask.ca/About-WSA/Publications/25-Year-Water-Security-Plan/.

Shafer, J. M., & Labadie, J. W. (1978). Synthesis and calibration of a river basin water management model (Vol. 89). Colorado Water Resources Research Institute.

Shah, S.M.A., Razavi, S., Slaughter, A., Do, N.C., Carlson, H., Keshavarz, K., Eamen, L., Elshorbagy, A., Wheater, H., and Asadzadeh, M. (Under review). Integrated Modelling and Management of Complex Transboundary River System. Water Resources Management.

Sherafatpour, Z., Roozbahani, A., & Hasani, Y. (2019). Agricultural Water Allocation by Integration of Hydro-Economic Modeling with Bayesian Networks and Random Forest Approaches. Water Resources Management, 33(7), 2277-2299.

Shourian, M., & Mousavi, S. J. (2017). Performance assessment of a coupled particle swarm optimization and network flow programming model for optimum water allocation. Water Resources Management, 31(15), 4835-4853. https://doi.org/10.1007/s11269-017-1781-8

Sieber, J. & Purkey, D. (2015). Water Evaluation And Plannin System User Guid. Stockholm Environment Institute, U.S. Center.

Sonis, M., & Hewings, G. J. (1998). Temporal leontief inverse. Macroeconomic Dynamics, 2(1), 89-114.

Souza da Silva, G. N., & Alcoforado de Moraes, M. M. G. (2018). Economic water management decisions: trade-offs between conflicting objectives in the sub-middle region of the São Francisco watershed. Regional environmental change, 18(7), 1957-1967. https://doi.org/10.1007/s10113-018-1319-5

Statistics Canada. (2020a). Table 38-10-0041-01 Water intake in manufacturing industries, by source and by provinces, territories and drainage regions (x 1,000,000). https://doi.org/10.25318/3810004101-eng

Statistics Canada. (2020b). Table 38-10-0038-01 Water use parameters in manufacturing industries, by provinces, territories and drainage regions (x 1,000,000). https://doi.org/10.25318/3810003801-eng.

Statistics Canada. (2019a). Catalogue 15-602-X. Supply and Use Tables, Summary Level. Ottawa, Canada. https://www150.statcan.gc.ca/n1/pub/15-602-x/15-602-x2017001-eng.htm. Accessed May 2019.

Statistics Canada. (2019b). Table 36-10-0223-01: Implicit price indexes, gross domestic product, provincial and territorial. Retrieved from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610022301. Accessed May 2019.

Statistics Canada. (2018a). Catalogue 15-602-X. Supply and Use Tables, Summary Level. Ottawa, Canada. https://www150.statcan.gc.ca/n1/pub/15-602-x/15-602-x2017001-eng.htm. Accessed March 2018.

Statistics Canada. (2018b). Table 32-10-0406-01: Land Use. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210040601. Accessed April 2018.

Statistics Canada. (2018c). Table 38-10-0241-01: Total area that received irrigation by crop type. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810024101. Accessed April 2018.

Statistics Canada. (2018d). Catalogue 98-301-X2016001. Dictionary, Census of Population, 2016. Ottawa, Canada.

Statistics Canada. (2018e). Table 36-10-0455-01: Experimental domestic trade flow estimates within and between greater economic regions. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610045501. Accessed July 2018.

Statistics Canada. (2018f). Table 38-10-0250-01: Physical flow account for water use. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810025001. Accessed June 2018.

Statistics Canada. (2018g). Table 36-10-0487-01: Gross domestic product (GDP) at basic price, by sector and industry, provincial and territorial. Retrieved from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610048701. Accessed July 2018.

Statistics Canada. (2018h). Table 38-10-0038-01: Water use parameters in manufacturing industries by drainage regions. https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3810003801. Accessed October 2018.

Statistics Canada. (2018i). Table 32-10-0413-01 Irrigation in the year prior to the census. https://doi.org/10.25318/3210041301-eng. Accessed May 2018.

Statistics Canada. (2017a). Catalogue 98-316-X2016001. 2016 Census of Population. Ottawa, Canada. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/download-telecharger/comp/page_dl-tc.cfm?Lang=E. Accessed June 2018.

Statistics Canada. (2017b). Catalogue 16-201-X. Human Activity and the Environment: Freshwater in Canada.

Statistics Canada. (2011). Catalogue 16-401-X. Industrial Water Use.

Statistics Canada. (1985). Catalogue 15-201E. The input-output structure of the Canadian economy, 1979-1981. Ottawa, Canada.

Strzepek, K. M., Yohe, G. W., Tol, R. S., & Rosegrant, M. W. (2008). The value of the high Aswan Dam to the Egyptian economy. Ecological Economics, 66(1), 117-126. https://doi.org/10.1016/j.ecolecon.2007.08.019

Tanoue, M., Taguchi, R., Nakata, S., Watanabe, S., Fujimori, S., & Hirabayashi, Y. (2020). Estimation of direct and indirect economic losses caused by a flood with long-lasting inundation: application to the 2011 Thailand flood. Water Resources Research, 56(5), e2019WR026092. https://doi.org/10.1029/2019WR026092

Tate, D. M. (1986). Structural change implications for industrial water use. Water Resources Research, 22(11), 1526-1530. doi:10.1029/WR022i011p01526

Teotónio, C., Rodriguez, M., Roebeling, P., & Fortes, P. (2020). Water competition through the 'water-energy'nexus: Assessing the economic impacts of climate change in a Mediterranean context. Energy Economics, 85, 104539. https://doi.org/10.1016/j.eneco.2019.104539

Töyrä, J., Pietroniro, A., & Bonsal, B. (2005). Evaluation of GCM Simulated Climate over the Canadian Prairie Provinces. Canadian Water Resources Journal, 30(3), 245-262. https://doi.org/10.4296/cwrj3003245

United Nations. (2015). General Assembly. Office. https://doi.org/10.1017/S0020818300007499

United Nations (UN). (1992). The Dublin Statement on Water and Sustainable Development. United Nations International Conference on Water and the Environment. Retrieved from http://www.un-documents.net/h2o-dub.htm.

UNESCO Working Group M.IV. (1999). Sustainability Criteria for Water Resources Systems. Cambridge University Press.

Velázquez, E. (2006). An input-output model of water consumption: Analysing intersectoral water relationships in Andalusia. Ecological Economics, 56(2), 226–240. https://doi.org/10.1016/j.ecolecon.2004.09.026

Vogel, R. M., Lall, U., Cai, X., Rajagopalan, B., Weiskel, P. K., Hooper, R. P., & Matalas, N. C. (2015). Hydrology: The interdisciplinary science of water. Water Resources Research, 51(6), 4409-4430. https://doi.org/10.1002/2015WR017049

Wang, L., Fang, L., & Hipel, K. W. (2008). Integrated hydrologic-economic modeling of coalitions of stakeholders for water allocation in the South Saskatchewan River Basin. Journal of Hydrologic Engineering, 13(9), 781-792.

Ward, F. A., Mayer, A. S., Garnica, L. A., Townsend, N. T., & Gutzler, D. S. (2019). The economics of aquifer protection plans under climate water stress: New insights from hydroeconomic modeling. Journal of Hydrology, 576, 667-684.

Ward, F. A. (2014). Economic impacts on irrigated agriculture of water conservation programs in drought, Journal of Hydrology, 508, 114–127. https://doi.org/10.1016/j.jhydrol.2013.10.024

Ward, F. A. (2009). Economics in integrated water management. Environmental Modelling & Software, 24(8), 948-958. https://doi.org/10.1016/j.envsoft.2009.02.002

WCED. (1987). Report of the World Commission on Environment and Development : Our Common Future Acronyms and Note on Terminology Chairman â€TM s Foreword. Report of the World Commission on Environment and Development: Our Common Future, 1–300. https://doi.org/10.2307/633499

Wheater, H., & Gober, P. (2013). Water security in the Canadian Prairies: science and management challenges. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371: 20120409. https://doi.org/10.1098/rsta.2012.0409

Wheaton, E., Wittrock, V., Kulshreshtha, S., Koshida, G., Grant, C., Chipanshi, A., Bonsal, B., Adkins, P., Bell, G., Brown, G., Howard, A., and MacGregor, R. (2005). Lessons Learned from the Canadian Drought Years 2001 and 2002: Synthesis Report. Prepared for Agriculture and Agri-Food Canada. SRC Publication No. 11602-46E03. Saskatchewan, Canada.

White, D. J., Feng, K., Sun, L., & Hubacek, K. (2015). A hydro-economic MRIO analysis of the Haihe River Basin's water footprint and water stress. Ecological Modelling, 318, 157–167. https://doi.org/10.1016/j.ecolmodel.2015.01.017

Williamson, O. E. (1994). Transaction cost economics and organization theory. In N. J. Smelser, & R. Swedberg

(Eds.), The handbook of economic sociology (pp. 77–107). Princeton, NJ: Princeton University Press.

Wittrock, V., & Wheaton, E. (2007). Towards Understanding the Adaptation Process for Drought in the Canadian Prairie Provinces: The Case of the 2001 to 2002 Drought and Agriculture. Saskatchewan Research Council, Saskatoon, Saskatchewan. Canada. SRC Publication No. 11927-2E07.

Wood, R. (2011). Construction, stability and predictability of an input–output time-series for Australia. Economic Systems Research, 23(2), 175-211.

Yang, Y. C. E., Brown, C., Yu, W., Wescoat Jr, J., & Ringler, C. (2014). Water governance and adaptation to climate change in the Indus River Basin. Journal of Hydrology, 519, 2527-2537. https://doi.org/10.1016/j.jhydrol.2014.08.055

Yoo, S., & Yang, C. (1999). Role of Water Utility in the Korean National Economy. Water Resources Development, 15(4), 527–541. https://doi.org/10.1080/07900629948745

Zhang, C., & Anadon, L. D. (2014). A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecological Economics, 100, 159-172. https://doi.org/10.1016/j.ecolecon.2014.02.006