Water Allocation in Southern Alberta

By

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Degree in Public Policy and Administration

Carleton University
Ottawa, ON

2020

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Abstract

This dissertation examines water allocation in southern Alberta and develops a fungibility framework for water rights and examines a range of characteristics impacting the transferability of water rights in southern Alberta. Fungibility is the degree to which water rights are homogenous. The fungibility of water rights is impacted by the number of different water rights within a given basin, the way these rights are defined, limitations on their transferability and how secure they are. Recognizing the characteristics that impact fungibility and ensuring water rights are as homogenous as possible makes these water rights easier to transfer between water users and may ensure a more effective water transfer system in southern Alberta. Even though water license transfers have been limited in terms of amount and volume, the total economic benefit from water use in the South Saskatchewan River Basin can increase through water reallocation. This dissertation illustrates how, without institutional constraints, basin-wide economic benefits could increase and shows what a potential reallocation of water allocations in the region looks like. This reallocation could see more water diverted to municipal users at the expense of agricultural users. Finally, the political influence of irrigators is examined. Efforts at reallocating water away from irrigation will be limited unless coalitions develop that can minimize the influence of irrigation's proponents.

Acknowledgements

First and foremost, I would like to thank my thesis supervisor, Prof. Stephan Schott, for all his support and guidance. His insights, encouragement and ability to keep me on track were instrumental throughout the duration of this work. He always provided me with useful advice and comments on how to best improve my work. Thank you for your patience and guidance.

Prof. Stanley Winer and Dr. Robert Slater were also very important for the completion of this work. Prof. Winer helped clarify my thoughts and develop my ideas and his feedback was instrumental throughout this process. Dr. Slater's vast experience in water management ensured my focus never strayed too far from the political realities constraining water governance. Again, I would like to thank them both for their patience and guidance throughout this process. I would also like to thank my examiners, Prof. Inger Weibust and Prof. John Janmaat for their considered and thoughtful comments that have improved this dissertation.

Finally, I would like to thank my friends, colleagues at Carleton, and family, especially my parents for their constant support and encouragement. I would especially like to thank Kate Guse, without whose constant encouragement, I would not have been able to finish this work.

Table of Contents

<i>Abstract</i>	<i>ii</i>
<i>Acknowledgements</i>	<i>iii</i>
<i>List of Tables</i>	<i>vii</i>
<i>List of Figures</i>	<i>viii</i>
1. Dissertation Overview	10
1.1. Introduction	10
1.2. Problem Statement	11
1.3. Dissertation Structure	12
1.4. Background and Themes	13
Geographic Background	13
Political Economy	15
Institutional Layering	16
Efficiency	18
Water Markets	20
Institutional Stability	21
Advocacy Coalitions	23
1.5. Methods	23
Data Sources	24
Chapter Two Outline	25
Chapter Three Outline	26
Chapter Four Outline	28
1.6. Caveats	29
First Nations	32
1.7. Thesis Overview	33
References	35
2. Layers of Change: A Historical Institutional Analysis of Water Governance in Southern Alberta	39
1. Introduction	39
2. Misaligned allocation regime	43
2.1. Institutional Origins	44
2.2. A Shifting Policy Orientation	48
3. Fungibility	52
4. Potential Solutions	62
4.1. Sharing Scarcity	62
4.2. Consumptive Water Use	64
5. Conclusion	65
References:	68
3. Allocating Water in Southern Alberta: A Quadratic Programming Model	74

1. Introduction	74
2. The Current Water Allocation in the SSRB	76
3. The SSRB Water Allocation Model	77
3.1. Economic Demand and Return Flows	83
3.2. Institutional Representation	86
4. Results and Discussion	87
4.1. Alternate Allocations	89
4.2. Interpretation	95
5. Conclusion	100
References:	102
4. The Political Incentives of Water Allocation in Southern Alberta	106
1. Introduction	106
2. A Narrative of Events	108
2.1. State Support of Irrigation	113
3. Modeling	116
3.1. Interplay with Electoral System	121
3.2. Political Incentives	122
4. The Political Game	124
4.2. Game 2 – Impact of Advocacy	129
4.3. Implications	132
5. Conclusion	136
References:	139
Chapter 5: Conclusion	142
1. Introduction	142
2. Dissertation Review	143
3. Chapter Summary	147
4. Implications	149
5. Recommendations	154
6. Final Remarks	156
References:	158
Appendix 1	159
Object-Oriented Programming Framework	159
AQUARIUS model architecture	161
Specifying Water Demand	162
Mathematical Connectivity	164
AQUARIUS Source Code	168
References:	170

List of Tables

TABLE 1: PROPERTY RIGHTS TO SURFACE WATER IN ALBERTA	63
TABLE 2: METHODS BY WHICH WATER IS ACQUIRED WITHIN AN IRRIGATION DISTRICT	64
TABLE 3: ALLOCATED FLOWS AND ECONOMIC BENEFITS UNDER CURRENT ALLOCATION	102
TABLE 4: AQUARIUS RESULTS AND SIMULATIONS	106
TABLE 5: SSRB WATER SUPPLY AND STEERING COMMITTEE WATER DEMAND PROJECTIONS (2009)	107
TABLE 6: PREFERENCE RANKINGS FOR IRRIGATORS AND OTHER WATER USERS	148
TABLE 7: PREFERENCES OF IRRIGATORS (F) AND NON-IRRIGATORS (U)	151

List of Figures

FIGURE 1: THE SOUTH SASKATCHEWAN RIVER BASIN (ALBERTA ENVIRONMENT, 2008)	46
FIGURE 2: PREFERENCES OF STAKEHOLDERS IN SOUTHERN ALBERTA	58
FIGURE 3: SSRB REPRESENTATION IN AQUARIUS	92
FIGURE 4: MONTHLY MARGINAL VALUE OF WATER IN RED DEER	106
FIGURE 5: MONTHLY MARGINAL VALUE OF WATER IN CALGARY	106
FIGURE 6: PAYOFFS WITH INCREASING RETURNS TO SCALE	131
FIGURE 7: THE COLLUSION GAME (BATES ET AL., 1999)	138
FIGURE 8: WATER POLICY CHOICE UNDER UNCERTAINTY	147
FIGURE 9: WATER POLICY WITH ADVOCACY GROUPS	152
FIGURE 10: AQUARIUS STRUCTURE (DIAZ ET AL., 2000)	183
FIGURE 11: AQUARIUS WATER SYSTEM COMPONENTS (DIAZ ET AL. 2005)	184

1. Dissertation Overview

1.1. Introduction

This dissertation is about water allocation and governance. It examines these topics in southern Alberta and from different perspectives such as historical institutionalism, natural resource economics and political economy, that overlap with considerations of water management and water policy. This dissertation examines how institutional design, electoral incentives and path dependency impact water allocation among competing users and proposes mechanisms to address current water supply problems.

Water allocation in southern Alberta is a distinct policy environment to that of northern Alberta (Heinmiller, 2016). Southern Alberta is home to 70% of Canada's irrigation output. Irrigation is the dominant water user and accounts for the majority of licensed water use (Alberta Agriculture and Forestry, 2015; Bennett et al., 2017; L. A. Nicol & Klein, 2006)). Southern Alberta receives an average of less than 500mm in precipitation annually and is one of the few regions with a semi-arid climate in Canada (Tanzeeba & Gan, 2011). This average is variable, with extremely wet years, such as 2005 and 2013, resulting in extensive flooding and extremely dry years, such as 2000, 2001 and 2015 resulting in water shortages and depleted rivers throughout the region (Heinmiller, 2016).

Northern Alberta's challenges with respect to water allocation, such as pollution and loss of habitat from oil sands mining involve a different set of actors such as oil and mining companies (Heinmiller, 2016). The water policy environment in northern Alberta is also much newer and developed alongside the development of the oil sands (Heinmiller, 2016) while southern Alberta's water policy developed as part of Canada's expansion and settlement objectives in the

late 19th century (Schmidt, 2011). The focus of this study is on water allocation and water policy in southern Alberta.

1.2. Problem Statement

Water is fundamental to the survival and prosperity of human beings and the environment. Due to concerns with the increasing scarcity of water resources, degradation of the water environment and climate change, more and more public attention and academic research is being devoted to water resource management and policies, including water allocation. One aspect of water management in southern Alberta is the definition of water rights and the possible reconciliation of indigenous rights to water with the prevailing water allocation regime established in the late 19th century. The goal of this research is to examine how the institutional origins of water allocation regimes constrain contemporary institutional outcomes with respect to water allocation.

By 2050, water demand is projected to increase by 55% globally (*Earthscan Studies in Natural Resource Management*, 2016). Under some climate change scenarios each degree of warming is expected to increase atmospheric moisture by 6-7% (*Earthscan Studies in Natural Resource Management*, 2016). These conditions would cause faster evaporation, larger water losses through evaporation and a greater risk of drought. The South Saskatchewan River Basin (SSRB) is a major agricultural basin in Alberta with a semi-arid climate and where 86.5% of agricultural production is reliant on surface water resources (Tanzeeba & Gan, 2011). The SSRB's population, which was 1,652,410 in 2006 is projected to grow to 2,594,039 in 2030 (Alberta Environment, 2008). Total water use was 1,981,000 dam³ (decameters³) in 2006 and total water demand is expected to reach

¹ 1 decameter = 10 meters

3,037,000 dams by 2030 (Alberta Environment, 2008). Alberta had a 6% decline in farms from 2011-2016 (Alberta Government, 2017) but acreage for irrigation districts is expected to increase (Bennet et al., 2017). These trends indicate that farms may get larger while employing less people.

This dissertation asks three major questions and answers them in the next three chapters. The three questions are:

- a) Why have water license transfers in the SSRB been an ineffective water sharing tool?
- b) What is the efficient allocation of water resources in the SSRB?
- c) What factors have allowed the current allocation of water – namely the primacy of irrigation – to persist over time?

While these are the three major lines of inquiry in the three papers, they are not the only questions. Each paper will address numerous sub-questions that will be discussed in greater detail in the chapters themselves.

1.3. Dissertation Structure

This dissertation is structured as an introduction, three chapters and a conclusion. Chapters two, three and four can be read as individual manuscripts that address one of the major lines of inquiry outlined above. This chapter describes the methods used, the scope of this research, and previews the work in each of the three chapters. In addition, a background and introduction to the themes that recur throughout the following chapters is provided.

1.4. Background and Themes

Several key themes are found throughout this dissertation: institutional layering, water use efficiency, institutional stability and transition. Alberta's water governance regime is a layered regime, where new institutional layers and mechanisms have been added without dismantling pre-existing arrangements and without rationalizing the institutional structure as a whole (Mahoney & Thelen, 2010; Schickler, 2001). The layering of different policy objectives results in institutional incoherence (Schickler, 2001). This dissertation offers insight into how and why Alberta's water allocation regime is layered in a sedimentary fashion and explores the tensions between contemporary policy goals and historical developments.

Geographic Background

A study of water management in southern Alberta is ostensibly a study of water management in the South Saskatchewan River Basin (SSRB). The SSRB is a tributary basin of the Nelson River system which drains into Hudson Bay. The basin originates in the Rocky Mountain Continental Divide in Alberta and stretches across southern Alberta into south-central Saskatchewan where the South Saskatchewan River joins with the North Saskatchewan River, forming the Saskatchewan River (Alberta Environment, 2008). The climate of the basin is semi-arid where summer is short with mean temperatures varying between 14 to 16°C and winter is long with mean temperatures varying between -2.5 to -8.0°C (Tanzeeba and Gan, 2011). Median temperatures in the SSRB range between 6 to 16 °C (AMEC, 2009) with extreme temperatures varying between 40°C in summer months and -40°C in the winter months (Tanzeeba and Gan, 2011).

The SSRB has four sub-basins; the Red Deer, the Bow, the Oldman River and the South Saskatchewan sub-basins (Alberta Environment, 2008). The total drainage area of the SSRB in Alberta is 112,800 km² and the median annual flow is 8,842,000 dam³. Annual precipitation in the basin varies spatially and is between 200 mm and 500 mm (Tanzeeba & Gan, 2011). Most of the annual precipitation is in the form of rainfall but most of the surface water flow in the basin comes from the spring snowmelt. About 70% of the annual runoff of the rivers is supplied from the Rocky Mountains and the foothills (Tanzeeba & Gan, 2011).

Temperatures in southern Alberta have increased by 1.9°C between 1948-2016 (Climate Atlas of Canada, 2019). This increase in temperature is greater than any other region of Canada. Average temperatures increased by 3.1°C in the winter and 1.1° during the fall months (Climate Atlas of Canada, 2019). Even though southern Alberta, and the Prairies as a whole, have experienced the highest increases in mean temperature over the 20th century, mean temperatures are expected to increase further (Climate Atlas of Canada, 2019). Compared to the baseline temperatures of 1986-2005, climate projections predict a 1.5°C increase in mean temperatures between 2031-2050 under a low carbon emission scenario. Mean temperatures in southern Alberta are projected to increase by 2.3°C for a high emission scenario during the same time span (Climate Atlas of Canada, 2019).

Coupled with these increases in temperature is an increased variance in precipitation. Low carbon emission projections predict a 5% increase in precipitation in the Prairies from 2031-2050, while high emission scenarios predict the increase to be as great as 6.5% (Climate Atlas of Canada, 2019). These projections, along with the predicted temperature increases, could lead to

greater evaporation and a greater frequency of droughts. Lower summer streamflows for the rivers are expected as result throughout the Prairies, if these projections prove to be accurate (Climate Atlas of Canada, 2019).

The SSRB is home to 65% of all irrigated land in Canada. In addition, 75% of consumptive water use in the SSRB is from irrigation (Bjornlund, Xu, et al., 2014; L. A. Nicol & Klein, 2006). Since the 1800s, water has been steadily allocated to water users in agriculture, industry and municipalities using a priority system (Pentney & Ohrn, 2008). From a water management perspective, the development of irrigation in the SSRB is of great importance as it accounts for approximately 75% of the total volume of water allocated (L. Nicol et al., 2010; Pentney & Ohrn, 2008; Russenberger et al., 2011).

Political Economy

Access to natural resources can be interpreted as the struggle between different societal actors to establish, maintain or increase their share of the material wealth created by resource extraction and use (Hessing et al., 2005). A political economy analysis of water policy in southern Alberta requires a knowledge of the economic interests within the policy subsystem and an understanding of what actors and processes are competing for with respect to water use (Hessing et al., 2005). This analysis of water allocation in southern Alberta is rooted in political economy and reveals the conditions under which water policy decisions take place, as well as the consequences of these decisions. This focus on the broader political economy of southern Alberta provides a better understanding of the motives of different actors and insights into what future water policy changes may look like.

Water allocation, in this dissertation, is understood as a process that is driven by the economic and political context in which it is situated. In southern Alberta's water policy subsystem, the conflicting actors and their incentives are explored. This dissertation assumes the interests and perspectives within the subsystem are materially grounded in the activities of social actors (Hessing et al., 2005). The conflicting interests among different actors, with respect to water policy, is emphasized in this analysis. Conflicts and challenges associated with water allocation are understood to emanate partly from economic and political exchanges between actors (Hessing et al., 2005). The interests of these actors can be conflicting as a result of their differential standing with respect to the costs and benefits of their interactions with the prevailing institutional arrangements.

Institutional Layering

Central to this undertaking is an appreciation of how the institutions governing water in Alberta – both currently and in the past – function. Institutional layering exists within the broader historical institutionalist framework and focuses on formal institutions to explain the process of institutional change (Streeck and Thelen, 2005). Using southern Alberta's water policy subsystem as a case, this dissertation explores the concept of layering and considers the context in which institutional arrangements are shaped by their social, political and environmental contexts (Thelen, 1999). Institutional layering was popularised, defined and developed by Kathleen Thelen to explain gradual institutional transformation. Layering is a process in which new elements are attached to existing institutions and gradually change their status and structure (van der Heijden, 2011). These new elements do not replace the old institutional arrangements or structure. Layering asserts that the existing institutional arrangements are not replaced when new

institutional layers – which might be rules, policy processes or new actors – are added to them (Streeck et al., 2005; Thelen, 1999).

Institutional layering is also a path dependent process (Pierson, 2004). Any new institutional layers will not displace what came before, including southern Alberta's colonial history with respect to settlement and the allocation of water rights. The options available to decision makers depend on the choices already made in the past. Institutions develop through an accumulation of innovations that are driven by competing motives, which results in a layering of new arrangements on top of pre-existing structures (van der Heijden, 2011). While each individual change is designed to serve specific goals, the layering of successive arrangements usually results in institutions that appear haphazard (Streeck et al., 2005).

This dissertation traces the origins and development of southern Alberta's water institutions and explores how earlier water policies and legislation make the cost of change very high. The entrenchment of certain institutional arrangements obstructs the reversal of initial policies (North, 1990). Institutions induce self-reinforcing processes that make reversals unattractive over time (Pierson, 2004). In the presence of these self-reinforcing processes, the probability of institutional change declines. This occurs because the relative benefits of pursuing activities under the current institutional arrangements compared with alternative options increases over time (Pierson, 2004).

The focus on institutional layering provides an opportunity to consider water policy as a product of history and path dependence. Water institutions and regimes are often considered as a

coherent whole (Streeck et al., 2005). From a policymaking perspective, it may be more explanatory to see these institutions as multilayered and comprised of a number of overlapping and contradictory stakeholder considerations (Boone et al., 2018). Conceptualizing Alberta's water institutions in this manner allows for the decomposition of the system into layered instruments with different policy objectives (Boone et al., 2018).

Efficiency

Alberta allocates water through prior allocation. The priority principle states “first in time, first in right” (FITFIR), signifying the first entity to apply for a license with the government receives a license to that water at the first exclusion of others during times of shortage (Percy, 1977). The development of prior allocation in Alberta is inexorably linked to the need to facilitate irrigation and settlement. FITFIR allowed irrigators to stake their claim early and guarantee a secure source of water in a semi-arid region (Heinmiller, 2016). FITFIR also has a distributive ethos – this mechanism granted water licenses to users willing to use water as opposed to those whose lands abutted a water body (Schorr, 2005). Water users only possessed usufructuary rights granted by the government and these licenses were granted for to encourage development, prevent the hoarding of water licenses by riparian landowners and advance claims of distributive justice (Schorr, 2005). Irrigation's importance to southern Alberta's early development resulted in the vast majority of senior licenses being owned by irrigators and irrigation districts.

The growth in municipal and industrial water demands put a strain on existing water supplies in southern Alberta as early as the 1920s (Percy, 1977). The competition between irrigation and other users existed not only in southern Alberta, but in semi-arid regions of the American West

(Bretsen & Hill, 2009). The solution was to increase the available water supply and facilitate the use of water resources for economic development (Schmidt, 2011). Municipal and industrial water demand continues to grow and create a gap between existing water supplies and forecasted demands (Goemans & Pritchett, 2014). In addition, the public demand for instream flow protection for environmental and recreational use are also increasing. The traditional approach to growing water demands – large scale water supply projects – is expensive and controversial as the environmental impacts of these projects have become better understood (Schmidt, 2011). Contemporary water policy, both in Alberta and other semi-arid jurisdictions, has shifted toward conservation and the reallocation of existing supplies (Donohew, 2009).

Two arguments are made in support of reallocation. The first posits that reallocating a relatively small proportion of water away from irrigation can lead to a significant increase in the amount of water available to other uses (Bretsen & Hill, 2009). The second argument is rooted in economic efficiency and argues that allocating water through FITFIR during shortages fails to allocate water to its highest valued use (Goemans & Pritchett, 2014). The marginal value of water fluctuates as new uses emerge, or as its availability is impacted by changing climatic conditions, market dynamics or evolving institutions. In an idealized setting, markets reallocate water to the highest valued use to maximize efficiency (Bretsen & Hill, 2009; Easter & Huang, 2014). Under FITFIR, when water availability is limited, Alberta's government allocates water to the most senior license holder first, regardless of the marginal value.

Alberta's *Water Act* introduced voluntary license transfers in 1999. Proponents of license transfers argue that transfers reallocate water licenses based on individual decision making in a

decentralized setting, incentivises conservation (Broadbent et al., 2017) and results in the efficient allocation of water (Horbulyk, 2005). However, maximizing aggregate efficiency does not address distributional concerns. This dissertation uses an optimization model to maximize the total economic benefits to water use in a basin and subsequently examines the implications of this allocation.

This dissertation examines what an idealized, efficient allocation of SSRB water resources looks like. An allocation of water resources is efficient if there is no redistribution of the resource that will create greater benefits for individual users without making at least one user worse off. This idealized, efficient allocation will be compared to the current allocation of water in the SSRB. Promoting efficiency and the use of water markets is a departure from the governance model espoused by the prior allocation regime and the development of southern Alberta's water institutions. The logic underpinning a water market is efficiency and a devolution of decision making where it is assumed that individual transactions will lead to the desired, societal outcome (Schmidt, 2011). Southern Alberta's allocation regime was designed to prevent private transactions and espoused a distributive, community-oriented water governance model (Schmidt, 2011; Schorr, 2005). Chapter two will discuss the ethics espoused by southern Alberta's allocation regime and the misalignment of the institutional structures with the new institutional layers introduced by the *Water Act*.

Water Markets

Alberta's *Water Act* (1999) allows for the voluntary exchange of water licenses without the exchange of land, under a limited set of conditions including a basin management plan. The

SSRB became the first watershed with such a management plan in 2002. This water market continues the tradition of valuing Alberta's water instrumentally, as a means of economic development (Schmidt, 2011). Initially, water was instrumental to Canadian sovereignty and western settlement and the SSRB basin management plan classifies southern Alberta's water allocation problems in primarily economic terms that can be addressed by a market mechanism (Schmidt, 2011). This mechanism seeks to address water management issues partly through individual transactions. The adoption of a water market reflects a broader trend towards devolving water management to include multiple stake holders globally. This devolution is referred to as going from "government to governance" and is aimed at improving efficiency (Schmidt, 2011). Some proponents of water markets believe that governments and administrative arrangements have sometimes allocated water through political considerations and have been historically inefficient (Dinar et al., 1997; Schmidt, 2011).

Institutional Stability

This dissertation argues that institutions induce choices that are made in equilibrium. In the absence of exogenous changes, the behaviour of actors is expected to remain unchanged (Schotter, 1981). Behaviour thus becomes stable and patterned. This conception of institutions draws on Andrew Schotter's notion of institutions as game-theoretic equilibria (Schotter, 1981). and is reliant on micro-level reasoning developed on the premise of rationality in choice (Bates, 1998). While Chapter two analyses the political economy of southern Alberta's water policy subsystem – and focuses on the interests of various coalitions – game theory is used in Chapter four to analyse why the current equilibrium, with respect to water allocation, might persist and how different types of coalitions could form.

In analyzing institutions, Chapter four uses concepts drawn from game theory, specifically games in extensive form. Chapter four seeks to explore a concrete, historical case of how water institutions developed in southern Alberta. In doing so, the choices of actors who are embedded in a specific setting and context are examined. The actions, decisions and responses that generate outcomes are explored. The actors explored in this manner possess preferences and expectations and are locked in patterns of strategic interdependence (Bates, 1998). The extensive form explicitly illustrates these features of southern Alberta's water allocation regime. The use of extensive form games necessitates the conception of equilibria in terms of subgame perfection. In extensive form games, a subgame is any part of the game in which behaviour can be analyzed independently from that in any other portion of the game (Bates, 1998).

Credible threats or promises are an essential feature of subgame perfect equilibria (Bates, 1998). For instance, an incumbent party may promote irrigation to avoid losing seats in the legislature because irrigators are regionally concentrated and could have significant influence in a first past the post electoral system. Fears or expectations of the consequences of straying of the equilibrium path encourage adherence to equilibrium behaviour. Credible threats and expectations of consequences thus play a significant role in generating institutionalized patterns of behaviour (Bates, 1998). Chapter four explores the source of institutional stability in southern Alberta's water allocation regime. In doing so, the interplay between politics and economics is explored.

Advocacy Coalitions

This dissertation assumes that policy development occurs within a policy subsystem – the water policy subsystem of southern Alberta (Heinmiller, 2013). The territorial boundaries of the subsystem are those of the province of Alberta (specifically the SSRB), which has constitutional jurisdiction over the allocation of water resources within its borders. Within this policy subsystem are the various actors – politicians, public servants, interest groups, journalists, scientists and private citizens – who claim an interest or a stake in the policy area and who regularly participate in water policy processes (Heinmiller, 2013).

The advocacy coalition framework (ACF) is a theory of the policy process that has existed since the late 1980s. It was developed by Paul Sabatier and Hank Jenkins-Smith. Heinmiller (2013, 2016) has used the ACF to explain how water policy in southern Alberta changed over time and what factors led to the enactment of the *Water Act*. According to the ACF, actors are driven by their policy beliefs and their desire to see their beliefs reflected in policy (Heinmiller, 2016). A group of actors who share a set of policy core beliefs and engage in collective action form an advocacy coalition (Heinmiller, 2013). This dissertation builds on Heinmiller's work by examining how different advocacy coalitions have led to a misalignment of policy objectives within the water allocation regime in Chapter two.

1.5. Methods

The methods of this dissertation are presented here in terms of the data used, the manner in which the analysis was conducted, and the fit of each methodological approach to each chapter.

Each of the subsequent three chapters can be read as a stand-alone manuscript and addresses a specific line of inquiry, with a different methodology deemed appropriate for the line of inquiry.

Data Sources

The data used for this dissertation comes from two sources. The first source, secondary historical material was gathered from an extensive literature review. Secondary historical material covered the evolution of Alberta's water laws, their relation to settlement objectives, governance and environmental history. These dimensions of Alberta's water institutions are essential to understanding the institutional origins and development of water allocation throughout southern Alberta's development and its current state in contemporary Alberta. The second source of data was from public documents. These documents include legislative documents governing water allocation such as the *Water Act* and the *Irrigation Districts Act*. Water transfer data from the Ministry of Environment and Parks and data on the transfer of irrigation acres from select irrigation districts was also collected. Results from previous studies and interview results from the Conference Board of Canada were also used. One implication of using government publications is that different ministries have different directives.

Chapter three develops an optimization model for water allocation in the SSRB. Water use data from municipalities and irrigation districts was used to develop this model. Data depicting municipal water use within the SSRB was collected from the 2011 Environmental Canada Municipal water use report. Data on water diversions from irrigation districts was collected from the Alberta Agriculture and Rural Development's annual reports on irrigation water use. The storage capacity of the reservoirs and lakes within the basin was estimated using the Atlas of

Alberta Lakes (Mitchell & Prepas, 1990) which is still used by Alberta Environment. For hydropower production, studies have used data on the average annual energy production and the regulated rate that is charged by utility providers. The Alberta Utilities Board has the required data, which is available through their reports, for hydropower depictions in the model. Data on water charges in cities was gathered from monthly consumption charges made publicly available by the utility boards of each city.

Chapter Two Outline

This chapter explores why water license transfers have remained a limited water sharing tool in southern Alberta. In considering the barriers to water license transfers, this chapter examines the water allocation regime as whole. Using a historical institutionalist framework, this chapter traces the historical origins of water institutions in southern Alberta and how the outcomes they elicited persist. The misalignment in objectives between the water allocation regime and the water transfer system – along with contradictory stakeholder positions within the subsystem – will be discussed in this chapter.

The rationale of Alberta's traditional approach to water governance and the rationale of the water license transfer system differ. This chapter, through the use of public documents and secondary historical material, critically assesses the policy orientations present in different institutional layers. Historical institutional analysis is used to analyze Alberta's water legislation and to identify politically contingent events and paths to show how pre-existing institutional structures shape contemporary institutional outcomes and paths for change (Boone et al., 2018; Thelen,

1999). In this case institutional outcomes include Alberta's *Water Act* and one specific policy instrument, water license transfers.

Chapter two posits and examines how the non-fungibility of water rights constrains water license transfers in southern Alberta. To examine this theory, this chapter develops a fungibility framework (Bradford, 2018) to compare a range of water right characteristics. In doing so, the degree to which water rights are heterogenous and non-transferable will be illustrated. Southern Alberta's water allocation regime is compared to the allocation regimes in Australia and Colorado across the range of characteristics identified through the framework. Comparing these allocation regimes provides insights on how to potentially harmonize water rights in southern Alberta and facilitate water transfers.

Chapter Three Outline

Chapter three uses a hydro-economic optimization model to determine the efficient water allocation in the SSRB under given constraints. The depiction of the SSRB in the model is an abstraction of the complexity in a watershed. The major municipalities, irrigation districts, instream protection zones are depicted in the model. The model architecture is spatially consistent with the SSRB and partitions the SSRB into its component sub-basins. Using this abstracted SSRB watershed, the current level of water allocation is depicted. The required data on water use and water demand for different water users was collected from a variety of sources. The AQUARIUS program (Diaz et al., 2000), which was developed by the US Department of Agriculture, was used to run the hydro-economic optimization model.

The objective function used in this study was the maximization of aggregate economic benefits from alternate water uses over a one-year period. Examining optimal water allocations over a one-year period is relevant for decisions involving water management and short-term water trading related to cropping and irrigation commitments (Cutlac & Horbulyk, 2010). In addition, a one-year optimization horizon can simulate how to efficiently deploy water storage reservoirs for reallocation across different water uses. Economic benefits are defined using demand curves which depict the willingness to pay for allocations of water to specific uses (Young & Gray, 1972). From a social welfare perspective, this exercise attempts to maximize the aggregate wealth in a system. Distributional and equity concerns are addressed through the iterative imposition of quantity constraints. The objective function uses sequential quadratic programming to maximize the sum of economic benefits from different uses. This objective function reallocates water to where its marginal value is highest, until the difference in marginal value of water among different uses is zero, subject to the quantity constraints imposed and net of transfer costs (Diaz et al., 2000).

The concept of efficiency is used around discussions of water management in southern Alberta. But what does efficient water use actually mean in this context? This chapter explores what this allocation, in theory, looks like. The chapter maintains the institutional constraints within southern Alberta – the prior allocation regime and the Master Apportionment Agreement between the Prairie provinces. This chapter assesses the potential welfare gains from reallocating water to where its marginal value is highest and assesses the impact of such a reallocation on different water users. These gains are optimized in a constrained modeling environment to mimic

both physical and distributional concerns. The implications of model results are discussed as well.

Chapter Four Outline

Given the potential to increase the economic gains from water use – through the reallocation of water – this chapter asks the question as to why the current allocation of water remains stable. The stability of the current allocation resembles an equilibrium where senior license holders hold the majority of water resources. Game theory is a powerful and frequently used approach to understanding the incentives natural resource users face (Galaz, 2004; Madani, 2010) and is used in this chapter. This approach is appropriate for analysing the strategic interactions of a limited number of actors involved in a purposeful action (Galaz, 2004). The analysis in Chapter four depicts the state, irrigators (senior license holders) and non-irrigators (junior license holders) as actors in a non-cooperative game. The use of game theory – to analyse the SSRB water market – rests on two fundamental assumptions. The first assumption acknowledges that water license holders in the SSRB are self-interested actors who respond to the incentives and information available to them. The second is a recognition that institutional arrangements that govern water allocation help structure the incentives of water users.

If the current allocation of water resources is indeed a stable equilibrium, it is because it is in the strategic interests of actors to maintain it. The reason this equilibrium is elicited will be explored. Proponents of water markets and license transfers have called for their expansion in southern Alberta (Cutlac & Horbulyk, 2010; Mahan et al., 2002). These proponents assert that a less burdensome transfer process will encourage more transfers between water users (Bjornlund, Zuo,

et al., 2014; Russenberger et al., 2011). By exploring the strategic interactions between water users and the incentives under equilibrium, this chapter puts these claims to the test. Scholars have observed that Alberta's water policy orientation has transitioned to a degree (Heinmiller, 2016; Schmidt, 2014). While new policy instruments have been introduced, the primacy of irrigation with respect to water allocation remains. By situating water policy within the economic and political context of the region, this chapter provides insight into how this current allocation is maintained and can potentially change.

An analytic model, using game theory, to examine the strategic behaviour of water users in the SSRB is developed. This analytic approach is combined with a narrative that pays close attention to the development and context of southern Alberta's water institutions. The use of an analytic model helps extract explicit and formal lines of reasoning (Bates, 1998), which facilitate an examination of why the current allocation persists and how alternative conditions will impact the behaviour of water users.

1.6. Caveats

There are several caveats attached to this dissertation. First, it is structured as a series of manuscripts. As such, there is a certain amount of repetition regarding some topics, such as the history of southern Alberta's water institutions, the origins of these institutions and the prominence of certain events. An effort has been made to emphasize different dimensions of these topics.

This dissertation focuses on formal institutional arrangements and the origins of these arrangements and does not fully examine other water governance principles and challenges such as those coming from First Nations within Alberta. All the ways First Nations and the Province of Alberta affect water governance and norms are not explored in this dissertation. In addition, this dissertation does not consider transboundary water governance issues, where water crosses political boundaries. With the exception of imposing a quantity constraint on an optimization model to mimic the minimum required flows into Saskatchewan, transboundary water issues are not explored. The objective of this work is to offer explanations for intra-provincial water governance issues and how governance norms and arrangements have been institutionalized. As such, there is no need to incorporate transboundary concerns, with the exception of including them as constraints on internal water governance.

Another limitation is the use of just one case, the water allocation regime in southern Alberta. This dissertation explores certain facets of this allocation regime, such as the barriers to water transfers or the impact of alternate water allocation mechanisms. The use of a historical institutionalist framework and Heinmiller's ACF show the origins, development and power dynamics that constrain contemporary outcomes. Game theory is used to model specific institutional arrangements found in southern Alberta. The absence of comparative work restricts the explanations and conclusions to this one case. When possible, the thesis engages in a broader contextualization of the Alberta case, but the place-specific nature of the Alberta context limits the reach of these findings. Chapter two provides a comparison with other water allocation regimes through a fungibility framework developed for water rights regimes.

The dissertation focuses on the allocation and governance of surface water. While Alberta's *Water for Life* strategy aspires to manage surface and groundwater holistically (Schmidt, 2011), Alberta's current water allocation system treats surface and groundwater differently. Surface water is governed under prior allocation while groundwater is governed by the "law of capture" (Brandes et al., 2008). The distinction is not scientifically based and does not reflect the reality that hydrologic systems are connected, and that surface and groundwater systems are connected in complex ways that are not fully understood (Brandes et al., 2008). This dissertation broadly focuses on the institutional arrangements governing surface water allocation in southern Alberta, and specifically on how prior allocation provides opportunities for, and constrains, water management now and in the future. The choice to omit groundwater analysis is necessary to understand the institutional origins of surface water governance in the region. In addition, there is no comprehensive inventory of Alberta's groundwater resources (Sproule-Jones et al., 2008). More monitoring and data collection are required to better understand the quantity and quality of groundwater resources in southern Alberta. It is estimated that groundwater accounts for 15% of water use in Alberta (Bennett et al., 2017). How changing climatic and market conditions will impact water resources in southern Alberta is not fully understood. Whether groundwater will be mined to supplement existing surface water resources or whether adaptive strategies based on sustainability and risk management will be implemented are open questions. Before developing adaptive water management strategies, the current state of water governance and its origins must be fully understood. Prior allocation was mostly concerned with the allocation of surface water and it is the reason why my attention is primarily concerned with it as well.

First Nations

The water claims of First Nations in Alberta precede those of the prior allocation regime (Schmidt, 2011). This implies that First Nations' claims to water are more senior than even the most senior water licenses under FITFIR. It is well documented that multiple First Nations occupied Alberta for millennia prior to European settlement (Phare, 2009; Schmidt, 2011). Through the subjugation of its indigenous peoples, southern Alberta – and the Prairies as a whole – was cleared for European settlement (Sproule-Jones et al., 2008). The federal government adopted a policy of economic development which determined who would benefit for the natural resources in the area, especially water. The primary beneficiaries of the federal government's early policies were settler ranchers and farmers and not the First Nations already present. This lack of acknowledgement did not deter First Nations from continually advancing their claims (Schmidt, 2011) and in 1925, leaders of the Tsuu T'ina nation publicly identified conflicts regarding prior allocation and water being valued as instrumental to land (Matsui, 2009). Elder Eliza Eagle Tail wrote that western techniques of valuing land and water in only instrumental terms ran counter to the indigenous view that the universe was delicately balanced and deserving of respect in its own right (Matsui, 2009). The privatization of land, and the early 20th century land grabs from Treaty 7 land, had the effect of continuing to subject First Nations' water rights to Canada's colonial impulse (Schmidt, 2011).

In tracing the institutional origins of Alberta's water allocation regime, this dissertation concedes that First Nations water rights are insufficiently reconciled under the current *Water Act*, and historically under the *Northwest Irrigation Act*. The treatment of First Nations under southern Alberta's water allocation regime is not explicitly addressed in this dissertation. Part of the

reasoning for this choice is to narrow the scope of this dissertation. Also, this dissertation attempts to understand the historical origins of southern Alberta's water policy subsystem. This subsystem emphasizes the narratives of irrigation districts and dominant players within the subsystem and, unfortunately, excludes the narratives of groups with countervailing histories (Schmidt, 2011) such as First Nations. Creating a legal and administrative regime which incorporates the rights and governance principles of First Nations in southern Alberta is a necessary step to including considerations of fairness and justice (Schmidt, 2011). However, this dissertation's focus is primarily on the regime itself, its limitations, its development and the various incentive structures that keep it in place. There is no doubt that changes will need to take place that recognize First Nations' rights, which is outside the scope of this dissertation, and subject to a complex negotiation process.

1.7.Thesis Overview

Chapter two explores why water license transfers have been a limited tool and examines the non-fungibility of water rights in southern Alberta. Chapter three develops a framework for integrating hydrological, environmental and economic factors into a regional scale water resource model is developed. The development of this modeling framework contributes to previous work on basin-wide water allocations studies in the SSRB (Weber & Cutlac, 2014; Cutlac & Horbulyk, 2010; He, 2012; Mahan, Horbulyk, & Rowse, 2002). This chapter examines whether a reallocation of resources will result in efficiency gains and assesses the extent of these gains. Chapter four introduces strategic behaviour on the part of water users and attempts to capture this behaviour through a game-theoretic model. The impact of changing economic and

political conditions are also examined to determine how the underlying incentives water users face can change.

Together, these chapters offer an explanation and analysis of how Alberta's water institutions developed and why new instruments such as water license transfers are likely to remain a limited, niche, tool for the region as it attempts to address its burgeoning water management issues. While the dissertation is tied to the narrative of how these institutions developed, insights on where southern Alberta's water policy is headed, potential policy tools to address misalignments and the non-fungibility of water rights are discussed.

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2. Layers of Change: A Historical Institutional Analysis of Water Governance in Southern Alberta

1. Introduction

Alberta's water allocation system is comprised of a centralized licensing regime which regulates usufructuary control of water resources. This allocation regime was designed to bring water management under the public sphere and incentivize irrigation and economic development in southern Alberta in the late 19th century by diverting water to valuable lands away from water sources (Schmidt, 2014). There were growing calls for irrigation support from settlers in response to a prolonged drought in the late 1880s in southern Alberta (Heinmiller, 2016).

Alberta's 1999 *Water Act* introduced new policy instruments to the existing water allocation regime such as voluntary water license transfers. Water license transfers were layered onto the existing water allocation regime in a sedimentary fashion (Heinmiller, 2016). Water license transfers show a departure in governing principles with respect to southern Alberta's traditional water management. These transfers continue and reflect the adoption of economic, user-driven instruments to manage water in southern Alberta.

Alberta's 1894 *Northwest Irrigation Act* vested all water in the property of the Crown (Schmidt, 2011) and made all water licenses appurtenant to the land tenure system devised under the *Dominion Lands Act* (Schmidt, 2011). The *Dominion Lands Act* parceled land in the prairies into 65-hectare plots and encouraged settlement along the course taken by the transcontinental railroad (Hedges, 1939; Schmidt, 2011). The architects of the *Northwest Irrigation Act* envisioned water development as a public enterprise to ensure Canadian sovereignty was achieved and because they felt privatization would result in only partial development of the

prairies (Schmidt, 2011). In addition, the concept of appurtenancy valued community interests far more than efficiency with respect to water use (Schmidt, 2011; Sax, 2008). Thus, the *Northwest Irrigation Act* was designed to reflect a collectivist perspective and facilitate national settlement objectives. Water transfers, which espouse individual transactions, are misaligned with the logic underpinning Alberta's historical water allocation principles.

This misalignment is illustrated by the non-fungibility of water rights in southern Alberta which can limit the scope of these water license transfers. This chapter examines the different water rights currently within southern Alberta and explores how their non-fungibility constrains the water market. These non-fungible water rights silo different water rights and users and limit water transfers. Limiting water transfers, and limiting the subsequent conservation holdbacks, undermines the new institutional layers introduced by the *Water Act*. The conservation holdback is the only provision in Alberta's water law which permits the reallocation of water from existing licenses to the environment (Heinmiller, 2016). Given the institutional arrangements, limiting transfers and holdbacks undermines any attempts at reallocation of current water allocations. Water license transfers were permitted in the South Saskatchewan River Basin (SSRB) in 2002. There have been 203 license transfers from the inception of this market until May 2017 (Alberta Environment and Parks, 2017), and the total volume of traded water constitutes just 0.00065% of the total licensed volume in the SSRB (Heinmiller, 2016).

A fungibility framework is developed to analyze how water rights within southern Alberta differ. A similar fungibility framework is used to examine energy systems (Bradford, 2018). Bradford's fungibility framework identifies four dimensions to the transformation of energy systems: i) the

type of energy; ii) where the energy is delivered to; iii) the timing of energy delivery; iv) and the certainty of energy delivery (Bradford, 2018). In the context of water rights, fungibility is the degree to which water rights are homogenous (Grafton et al., 2012; Squillace, 2012b; M. D. Young, 2015). Using this fungibility framework, a range of fungibility characteristic for water rights are developed. The degree to which water rights are fungible due to these characteristics in southern Alberta is examined. Policy recommendations are provided to address the lack of fungibility of water rights in southern Alberta.

The development of southern Alberta's water allocation regime is explored. Heinmiller's work on advocacy coalitions within southern Alberta's water policy subsystem illustrates the contradictory stakeholder considerations that shaped Alberta's *Water Act* (Heinmiller, 2013, 2016). Heinmiller (2016) points out that the *Water Act* was layered on top of Alberta's existing water allocation regime which was introduced by the 1894 *Northwest Irrigation Act*. While water legislation was amended throughout the 20th century, prior allocation and the water conveyance infrastructure it begat remained (Heinmiller, 2016). This outcome is the result of conflict between two coalitions: a coalition of irrigators and proponents of harnessing water resources for development purposes and a coalition of environmentalists who coalesced after Alberta's Progressive Conservative Party decided to construct a dam on the Oldman River in 1979 (Heinmiller, 2013; Sproule-Jones et al., 2008).

Thus, Alberta's water institutions resemble a multilayered historical composite (Schickler, 2001). The institutional layering that Heinmiller (2013, 2016) identifies is a conception within the historical institutional framework used to explain the process of institutional change (Streeck

et al., 2005; Thelen, 1999). The institutional layering literature conceives of institutions as distributional instruments laden with power implications (Mahoney & Thelen, 2010).

Institutional outcomes, such as the *Water Act*, are the outcome of conflict among groups or the result of compromises by actors who can have different substantive goals (Schickler, 2001). The layering literature asserts that institutions represent compromises that are built on coalition dynamics that are always vulnerable to shifts (Mahoney and Thelen, 2010; Thelen, 1999).

Heinmiller's advocacy coalition framework identifies the different coalitions within southern Alberta's water policy subsystem and shows how these coalitions mobilized their resources in pursuit of their preferred institutional outcomes (Heinmiller, 2013, 2016).

The next section examines how the water licence transfer system – introduced by the *Water Act* – is misaligned with the historical water governance principles in southern Alberta. To show this misalignment, the development of southern Alberta's water institutions and the impact of Heinmiller's advocacy coalitions on water policy within the region, is examined. This change resulted in the introduction of a water market within an institutional structure that was designed in an era where water license transfers were not conceived. One of the results of the layering of Alberta's water allocation regime is the non-fungibility of water rights. Section three builds on Heinmiller's work with respect to advocacy coalitions and introduces a fungibility framework to examine the degree of fungibility for water rights in southern Alberta. Section four proposes potential solutions to make water rights more fungible in southern Alberta and compares the allocation regimes of Australia and Colorado across a range of characteristics.

2. Misaligned allocation regime

A key feature of Alberta's water allocation regime is prior allocation or "first in time, first in right" (FITFIR). Prior allocation is the legal framework governing water allocation in Alberta and western Canada and was introduced to Alberta through the 1894 *Northwest Irrigation Act*. The prior allocation regime is a government-controlled system where water licenses are issued to individual (or collective) users for specific volumes and purposes. FITFIR signifies that the first person to apply for a water license with the government and receive a license to that water, receives the water at the first exclusion of others during times of shortage (Percy, 1977). During water shortages, water is progressively rationed by priority of license and diversions by junior license holders may be halted (Libecap, 2008). Prior allocation was maintained when Alberta assumed provincial control of its water resources through the 1931 *Water Resources Act* and after the *Water Act* was enacted.

The *Water Act* shifted the water policy orientation in southern Alberta (Heinmiller, 2016) and introduced several new policy instruments such as water license transfers, an eventual moratoria on the issuance of new water licenses in three out of four sub-basins of the SSRB, conservation holdbacks on water transfers (up to 10% of transferred volume is reserved for conservation purposes) and the ability of the Crown to reserve unallocated water for purposes such as instream protection or to provide water access to First Nation reserves (Heinmiller, 2013; Schmidt, 2011). The *Water Act* retained FITFIR as set out in the *Northwest Irrigation Act* and introduced the new policy instruments on top of the existing structure. This layered structure exhibits some tensions and Heinmiller (2013) asserts that the change in water policy orientation was the result of

conflict and compromise between two coalitions with different policy beliefs on how water should be used in southern Alberta (Heinmiller, 2013).

2.1. Institutional Origins

Southern Alberta was acquired by the Canadian government in 1870 as part of the Northwest territories. The federal government's priority was occupying and settling the territory, partly to foster economic development and partly to act as a bulwark against any northern expansion by the United States (Hedges, 1939; Schmidt, 2011). First Nations occupied the lands in the Prairies before the federal government facilitated the westward migration of Canadians and Europeans. The riparian rights regime, derived from English common law, was the water rights regime that was initially implemented in the prairies when settlers migrated westward (Scott, 2008). The riparian rights regime restricts water resource development to lands that abut or are adjacent to a river or stream (Brandes et al., 2008; Libecap, 2008). Water availability in southern Alberta was a major constraint on economic development. Alberta's SSRB (Figure 1) receives an average of less than 500mm in precipitation annually and is one of the few regions with a semi-arid climate in Canada (Tanzeeba & Gan, 2011). In a semi-arid region, the riparian rights regime was unsuited for maximizing the economic potential in water or to develop irrigation because potentially valuable non-riparian land could not be developed due to scarce water resources (Percy, 1977). Since the federal government wanted to facilitate intensive agriculture to foster an agrarian society in the prairies (Schmidt, 2011), riparian rights needed to be replaced with another allocation regime.

Riparian rights were deemed unsuitable in the American West as well (Reisner, 1993). In addition to limiting development, there were concerns over a monopoly of productive lands by riparian land owners (Schorr, 2005). FITFIR was developed in the American West to rectify

Figure 1: The South Saskatchewan River Basin (Alberta Environment, 2008)

these issues (Schorr, 2005). Legal disputes were a common way of establishing priority in the American West and to avoid these disputes the architects of the *Northwest Irrigation Act* adopted a centralized licensing system common in Australia and fused it with FITFIR (Schmidt, 2011).

The water allocation regime was designed to facilitate land development and foster settlement through irrigation (Heinmiller, 2016). Water was viewed as instrumental to these objectives (Schmidt, 2011). Water could be diverted to tracts of land where it was needed and be put to use, irrespective of whether these tracts abutted a river or stream. This fact, along with the

intermittent scarcity in the region, incentivized irrigators to “stake their claim early” and encouraged rapid development of irrigation (Heinmiller, 2016). These early irrigators received the earliest water licenses and had the most secure water rights in a regime where water was rationed by priority in times of scarcity. Two consequences of the prior allocation regime were the creation of a large water infrastructure network to divert water to non-riparian areas and the creation of a coalition of irrigators and senior license holders who had a vested interest in maintaining this developmentalist water policy orientation (Heinmiller, 2013).

Heinmiller (2013) documents the dominance of southern Alberta’s water policy subsystem by this coalition. This coalition was committed to a supply-driven water policy orientation and to preserving senior water licenses for irrigation. The shared beliefs of these actors and their willingness to pursue their beliefs through collective action makes them an advocacy coalition (Heinmiller, 2013, 2016). This coalition had considerable political influence in Alberta’s electoral system (Heinmiller, 2016). From 1975 to 2012, the irrigation belt consistently returned PC MLAs to the Alberta legislature, giving them strong representation in the party that governed the province continuously from 1971 to 2015 (Heinmiller, 2016). In the 1975 provincial election, the PCs were elected in 28/32 electoral divisions within the SSRB (Elections Alberta, 2019). In 1979, they were elected in 31 of those 34 divisions (Elections Alberta, 2019), cementing the relationship between the PCs and irrigators until the election of 2015. This electoral influence demonstrates Heinmiller’s “hard power resources” that were at the disposal of this advocacy coalition (Heinmiller, 2013).

Government support for irrigation went beyond legislation. Irrigators initially struggled in southern Alberta in the early 20th century (Klassen & Gilpin, 1999). These difficulties arose because of the high transaction costs involved in irrigation (Bretsen & Hill, 2007). High transaction costs arise in irrigation due to asset specificity and economies of scale (Bretsen & Hill, 2007). For example, the delivery of water to lands far from riparian zones requires a lot of infrastructure such as dams, reservoirs and canals. These structures are designed to deliver water to very specific locations and additional infrastructure is required to deliver water to other locations. To construct these structures on a regional scale required high start-up costs and organization capacity and only the state had the requisite organizational and financial capacity to facilitate irrigation at such a scale (Bretsen & Hill, 2007).

Private enterprises attempting irrigation struggled due to cost overruns, infrastructure failures and inexperience (Klassen & Gilpin, 1999; Rood, 2010). The 1915 *Irrigation Districts Act* empowered irrigation districts to issue bonds and finance the construction of irrigation works and to levy local taxes for the operation and maintenance of these systems (Klassen & Gilpin, 1999). Irrigation districts still struggled and received aid from the provincial and federal government in the form of loan guarantees (Smith, 1978). Several irrigation districts were run as Crown corporations, a practice that ended in 1974 (Smith, 1978). The economic depression and the terrible environmental impacts of the dustbowl in the region resulted in an increase of federal support for irrigation in southern Alberta (Klassen & Gilpin, 1999). Economically this period was a catastrophe for prairie farmers as wheat prices declined and the SSRB experienced a prolonged drought from 1929-1936 (Francis & Ganzevoort, 1980). Alberta was also bankrupted by the depression paving the way for a larger federal role in irrigation through the 1935 Prairie

Farm Rehabilitation Act (PFRA) (Heinmiller, 2016). Through the PFRA, the federal government directly funded the construction and maintenance of irrigation systems by spending around \$600 million on water infrastructure in the Canadian prairies, much of it directed to southern Alberta (Klassen & Gilpin, 1999).

In 1973, the federal government formally withdrew from its irrigation support activities (Klassen and Gilpin, 1999). Alberta's provincial government took up the mantle of irrigation supporter by acquiring and operating the headworks of the irrigation districts at no cost to the districts, making the 1970s a decade of unprecedented irrigation growth in southern Alberta (Heinmiller, 2013). From 1970 to 1979, the area of assessed irrigable land in the SSRB grew by 50 per cent, from 279,877 hectares to 419,730 hectares (Heinmiller, 2013). The provincial government also introduced a vastly expanded program to refurbish and expand the aging water infrastructure within the irrigation districts, with 86 per cent of the costs paid by the province and 14 per cent paid by the districts (Heinmiller, 2016). It is apparent that irrigation developed in southern Alberta in large part due to the assistance of the federal and provincial governments, who provided both legislative and fiscal support. Heinmiller's developmentalist advocacy coalition were not just in favour of irrigation, but favoured (and depended on) state support for the construction and maintenance of irrigation systems.

2.2. A Shifting Policy Orientation

Water shortages in the southern reaches of the SSRB in the late 1970s led proponents of irrigation to lobby the government for the construction of a dam on the Oldman River (Sproule-Jones et al., 2008). The Oldman River Dam was the largest and most expensive water project

ever undertaken by the province (Heinmiller, 2016; Schmidt, 2011; Sproule-Jones et al., 2008). The province's decision to construct the dam, despite widespread criticism from First Nations, environmentalists and the wider public underlies the dominance of Heinmiller's developmentalist coalition. The dam was built despite being recommended for decommission by an Environmental Assessment Panel and the fact that it invaded First Nations lands (Sproule-Jones et al., 2008). The government built this dam over the myriad of objections and protests to largely attract southern voters from the irrigation belt (Heinmiller, 2016) underlying this coalition's ability to leverage "hard power resources" (Heinmiller, 2013).

Heinmiller views the decision to construct the Oldman River Dam as a catalyst for change in southern Alberta's water policy (Heinmiller, 2013, 2016). In addition to generating widespread opposition, the Oldman River Dam prompted closer scrutiny of water allocation and governance policies in southern Alberta – policies that remained largely unchanged since the 1894 *Northwest Irrigation Act* (Heinmiller, 2016). Opposition coalesced into another, environmental, advocacy coalition comprised of environmentalists and conservationists (Heinmiller, 2013). The list of organizations in this coalition included: Friends of the Oldman Dam, Alberta Fish and Game Association, Ducks Unlimited, Alberta Wilderness Association, Alberta Environment Network and the Pembria Institute for Appropriate Development (Heinmiller, 2013). Unlike the developmentalist coalition, the environmental coalition had fewer costs associated with deviating from the traditional approach to governance but had very little electoral influence on government. The Alberta Green party has never won a seat in the Alberta legislature (Party was dissolved in 2009), ensuring that this new coalition had very few natural allies among the province's legislature and very limited "hard power resources" to leverage (Heinmiller, 2016).

Unlike irrigation and its proponents, members of the environmental coalition are not physically concentrated in one region (Heinmiller, 2016) and did not have the same impact on legislative seats within the province's electoral system. As a result, this coalition was forced to utilize soft power resources – the mobilization of public opinion – to persuade those in power to alter southern Alberta's water policy (Heinmiller, 2013).

The layering of Alberta's water allocation regime was not solely due to the conflict between two advocacy coalitions. While environmentalists and conservationists advocated for change, irrigators and other actors who benefited from the existing institutional arrangements were resistant because such change represented a loss of incumbent power – namely primacy within the water policy subsystem. When institutional arrangements appear fixed – as they did in southern Alberta despite a new advocacy coalition – new institutional layers are added to the pre-existing structure when the political environment is conducive to change (Hacker, 2005).

Heinmiller (2016) identifies the election of Ralph Klein in 1992 as the political window for change in Alberta's water policy orientation. Klein's government were determined to reduce the province's debt and proceeded to cut public sector jobs by 5 percent, eliminate over 1,000 public service positions and privatize several government functions such as the sale of alcohol (Rennie, 2004).

This impetus to reduce government spending invariably included costs within the water policy subsystem. The vast network of water conveyance infrastructure required to maintain irrigation was expensive to assemble and maintain. The Oldman Dam alone cost the Alberta government \$353 million in 1986 dollars (Parsons, 1994). Pressure for more demand-oriented water

governance from the environmentalist coalition and a government determined to reduce the provinces debt provided the necessary conditions for water policy to shift in southern Alberta (Heinmiller, 2016). Despite these conditions, irrigators and their proponents still possessed “hard power resources” and the suite of new policy instruments layered on top of the prior allocation regime were the result of compromises between coalitions with different substantive goals (Schickler, 2001).

The *Water Act* tried to address concerns regarding environmental protection, instream water levels and recreational water use (Schmidt, 2014). The *Water Act* gave the Crown the ability to reserve unallocated water for purposes such as instream protection or to provide water access to First Nation reserves (Heinmiller, 2013). The province also introduced the *Water for Life* strategy in 2003 and renewed it in 2008. This strategy was designed to ensure safe drinking water, healthy aquatic systems and a reliable water supply for a sustainable economy (Schmidt, 2011). A moratoria on new water licenses was also introduced in three of the four sub-basins of the SSRB (Bjornlund et al., 2014). Despite these changes FITFIR remained intact and the historical water use patterns of senior license holders largely remained unthreatened.

Irrigators and their coalition used their influence to avoid full-cost pricing in favour of water license transfers (Heinmiller, 2016). During the consultation process for the *Water Act*, the public was queried about their preference between water license trading and full-cost pricing. The results revealed that 32 per cent of respondents supported the introduction of water licence trading, while 85 per cent supported the introduction of full-cost pricing (Heinmiller, 2016). Full-cost pricing would have severely curtailed historical water use patterns because it would have

meant large water users in southern Alberta would have to bear the costs of water conveyance which were traditionally borne by the provincial government.

Southern Alberta's extensive water conveyance infrastructure was another impediment to change. According to Wilson (2015), infrastructure is the physical embodiment of ideas in water policy and may prove even more difficult to change for actors seeking to promote new priorities (Wilson, 2015). The lifetime replacement cost of Alberta's water conveyance infrastructure is \$5.9 billion – 75% of which is used for irrigation (Heinmiller, 2016). In addition, the average annual expenditure on rehabilitation of this irrigation infrastructure was \$31 million – 75% of which was paid for by the province (Heinmiller, 2016). For the environmental coalition, any efforts to mobilize public opinion promoting change is limited by the physical reality (Wilson, 2015) that the vast water conveyance infrastructure within southern Alberta was designed for irrigation and economic development purposes. In contrast, a water license transfer system where the distribution of water licenses was not changed protected historical patterns of use, did not require a fundamental realignment of infrastructure and converted senior water licenses into a valuable asset.

3. Fungibility

A key feature of Alberta's layered water allocation regime – especially in southern Alberta – is a misalignment of objectives. The government-controlled licensing system put water under the public sphere to harness water resources for settlement and development objectives (Schmidt, 2011). The suite of instruments introduced by the *Water Act* were demand-oriented instruments (Heinmiller, 2016). Water license transfers are voluntary, user-driven instruments consistent with

market principles (Easter & Huang, 2014). However, these market principles are radically different than the principles that governed water allocation in southern Alberta before the *Water Act*. Water allocation was always under the public sphere and was thought of as too important to be left to private individuals and private transactions (Schmidt, 2011). Introducing a policy instrument that was divorced from the underlying logic of the water allocation regime, introduced a degree of incoherence to water governance in southern Alberta.

The incoherence of the water allocation regime is most noticeable when looking at the different rights to water that exist in southern Alberta. For water transfers to function effectively, water rights have to be clearly defined and fungible (L. Crase et al., 2003; Libecap, 2008; Squillace, 2012). Fungibility is defined as the degree of homogeneity between water rights (Squillace, 2012), and captures the different dimensions by which water rights can be compared. The degree of fungibility of water rights is a direct consequence of the difficulty in defining clear property rights to water (Squillace, 2012) and in southern Alberta there are several fragmented rights to water (Bankes, 2006). In energy systems, the dimensions of fungibility include: what type of energy, where the energy is being delivered, the timing of energy delivery and the certainty across the aforementioned dimensions (Bradford, 2018). There are several obstacles to making water rights more fungible including provisions to protect third parties from the impact of water license transfers (Tisdell, 2014; Wheeler et al., 2014), the desire to maintain instream objectives within a basin (Schmidt, 2011) and any “no injury” provisions to protect the allocations of downstream or junior water users (Squillace, 2012). Given these considerations, a framework is developed to examine the characteristics of water rights in southern Alberta and how each characteristic impacts the fungibility of rights.

The first characteristic is the type of water right. Just like there are different forms of energy, there are different forms of water rights within a basin. In the SSRB, there are five types of water rights (Table 1). Secondly, there is the type of use specified by a specific water right. For example, a water license granted for irrigation is different to a water license granted for municipal use. The type of use impacts the amount of water consumed and hence the amount of water available to others. The third characteristic is how water rights are defined. A water right defined in terms of the consumptive amount is very different than a right defined as an absolute volume of water. The fourth characteristic involves the timing of water delivery. Some water rights require water at specific times of the year, such as irrigation and are sensitive to short term water shortages while others need a steady supply year-round. The use of storage capabilities has the potential to address this issue. In Australia water right holders can carry over their annual allocations for one year (Wheeler et al., 2014) and the ability to store these allocations is crucial.

Table 1: Property rights to water in Alberta

Type of Water Right	Features	Transferability
Pre-1999 Water License	<ul style="list-style-type: none"> • Most senior water rights. • Held by major municipalities and all 13 Irrigation Districts. • Perpetual Licenses that supersede the Water Act 	Transferable
Post-1999 Water License	<ul style="list-style-type: none"> • Governed by the Water Act. • Can be cancelled by the government • Have expiry dates 	Transferable
Traditional Agricultural User	<ul style="list-style-type: none"> • Appropriative Right • Introduced by the Water Act • TAUs can divert up to 6250 cubic meters of water annually • Perpetual 	Cannot transfer these rights
Domestic Water User	<ul style="list-style-type: none"> • Riparian Rights • Domestic Water Use • Groundwater use in some instances • 1250 cubic meters of water a year • Domestic use supersedes other uses statutorily 	Cannot transfer these rights
Subsidiary Rights under Irrigation Districts Act (2000)	<ul style="list-style-type: none"> • Governed by the Irrigation Districts Act (2000) • Can only be traded within an irrigation district • Not subject to any Water Act Regulations 	Can only be transferred within the boundaries of an irrigation district

The fifth characteristic is the transferability of the right. For example, subsidiary rights within irrigation districts are transferable within district boundaries but are not transferable across boundaries. The sixth characteristic concerns the delivery of water and whether there is the requisite infrastructure to deliver water to where it is needed. Finally, the fungibility of water rights is dependent on the certainty of a given water right. The certainty of a water right is impacted across the aforementioned characteristics and is also impacted by the climate, the level

of storage capabilities in a basin and the ability to leverage storage to carry over allocations. In addition, the presence of a priority system, coupled with climatic conditions, makes junior water rights relatively less certain than senior water rights. This framework is used to examine the fungibility of water rights in southern Alberta across the aforementioned range of characteristics. Table 2 presents the water allocation regimes of southern Alberta, the Murray-Darling basin (MDB) of Australia and Colorado's Big Thompson (CBT) basin. Each of these allocation regimes is assessed according to the range of characteristics impacting fungibility.

One type of water right in southern Alberta is a water license granted before 1999, when the *Water Act* came into force. A second type of right is a license granted after the *Water Act* was enacted. Water licenses granted after 1999 have expiry dates and are usually issued for 10 years or less (Bankes, 2006). Layering is encapsulated by this tiered system of water licenses where older licenses are exempt from some of the provisions of the *Water Act*, while newer licenses are not. The third right to water in southern Alberta is the right granted to traditional agricultural users (TAUs) (Sproule-Jones et al., 2008). The term refers to a user who, prior to 1999, diverted water for traditional agricultural purposes (Bankes, 2006). The fourth water right is that of riparian landowners and their right to domestic water use (Sproule-Jones et al., 2008). This situation differs in the MDB where each water entitlement is a share of the annual water availability (Commission, 2011). With respect to the type of water rights, water rights are more fungible along this characteristic in the MDB and the CBT because water rights are harmonized to be entitlement shares with differing magnitudes.

Water rights are used for different purposes across different jurisdictions. In the MDB, these access rights are unbundled from water use rights (Wheeler et al., 2014; M. D. Young, 2014, 2015). Unbundling water access and water use makes water transfers easier because rights can be held and transferred without a water use permit (M. D. Young, 2015). A water use permit is required if transferred water is to be used, but the unbundling of access and use rights makes the act of transferring water easier as the transfer does not automatically grant the right to use water, and a prospective user must demonstrate how they mitigate third party impacts. Alternatively, water rights were defined as proportional shares in the CBT because the water was always envisaged as supplemental to existing supplies (Carey and Sunding, 2001). Because this supplemental source is responsive to climatic conditions and homogenous for all shareholders, it is easier to transfer among water users.

There will always be heterogeneity with respect to when specific water users require water to be delivered to them. Agricultural areas will require water at specified times during a year and the timing of environmental flows is just as important as the amount of water set out for the environment. This heterogeneity with respect to the timing characteristic is common across all jurisdictions with different water uses. Conveyance infrastructure is a constraint on water use across all jurisdictions. To facilitate the development of agriculture in all three of these basins, the state undertook the construction of a vast water conveyance infrastructure to ensure water could be delivered to areas where users had water rights (Commission, 2011; Hanemann, 2014; Heinmiller, 2016; Reisner, 1993).

Water rights that are more fungible, are easier to transfer (Grafton et al., 2012; Squillace, 2012). Water rights in southern Alberta are not easily transferable. This lack of transferability is partly because there are five different types of rights. The fragmentation of water rights in southern Alberta constrains the water transfer system. In addition to water licenses, TAUs can also be transferred within the SSRB. However, TAUs can only be transferred between existing holders of the right and cannot be transferred to other right holders (Bankes, 2006). TAUs cannot be transferred to non-right holders because the right to codify these rights expired on December 31st, 2001. The TAU transfer system operates parallel to the water license transfer system, but the two rights systems are completely siloed and cannot be exchanged. Their non-transferability effectively confines each class of water right and the volume of water held under them from being exchanged.

Table 2: Characteristics Impacting the Fungibility of Water Rights Across Water Allocation Regimes

	Type of Right	Water Use	Right Definition	Timing	Transferability	Delivery	Certainty
SSRB	Five types of water rights	Rights specified for a specific type of use	Rights for a specified volume	Depends on water use	Different rights are siloed and cannot be traded with each other	Infrastructure needed for water delivery	Priority leaves senior rights more certain
MDB	All rights defined as entitlement shares with annual allocations based on climate	Use rights are unbundled from access rights	Rights defined as shares of total water availability	Depends on water use	Shares and annual allocations are transferable	Specific delivery right needed.	All shares proportionately reduced during scarcity
CBT	Water rights defined as proportional shares with annual allotments	Shares are supplemental sources for existing rights	Rights defined as shares of total water availability	Depends on water use. Supplemental rights.	Shares and annual allotments are transferable	Infrastructure needed for water transfers	All shares proportionately reduced during scarcity

Another impediment to transferability of water rights in southern Alberta are irrigation districts. The collective nature of their licenses adds another layer to the water rights system as no individual irrigator can transfer water outside of their district. The *Water Act* is not the only piece of legislation governing water use by irrigation districts. The *Irrigation Districts Act* (2000) governs water use within irrigation districts and introduces several other “subsidiary water rights” (Bankes, 2006; Bankes & Kwasniak, 2005), which make the water right system and ability to share water even murkier. The main form of subsidiary right created under this act is the right of ‘irrigation acres’ where an irrigator has the right to receive water for irrigation purposes (Bankes, 2006). Transfers of ‘irrigation acres’ within irrigation districts is not governed by the *Water Act* (Bankes, 2006) and these rights cannot be traded across district boundaries or between irrigators from different districts. The institutional structure, with respect to water right trades, is effectively siloed between license transfers, TAU transfers and transfers within district boundaries (Figure 2). For irrigation districts, assigning a part of their license to other uses appears to be the preferred instrument (Bennett et al., 2017). These assignments are essentially leases without regulatory oversight (Bankes & Kwasniak, 2005) where districts maintain long-term control of their water licenses and share water to other users.

Figure 2: Siloed Water Rights within SSRB

In contrast, water rights are defined as entitlement shares in the MDB and CBT and each user can transfer their share, either permanently or temporarily. The boundaries of irrigation districts are not boundaries to the transferability of shares in the MDB (Commission, 2011). All CBT shares are supplemental to existing water rights and are transferable either permanently or temporarily between shareholders (Carey and Sunding, 2001). Since CBT shares serve one irrigation district, transferability outside the district is not an issue (Carey and Sunding, 2001). Finally, the certainty characteristics of water rights is affected by climate and how this climate interacts with the water rights regime. A water rights regime with a priority system confers more certainty to senior water rights holders while a rights regime based on shares distributes this uncertainty equally among all water shareholders. Maintaining FITFIR ensures the certainty of water rights is not equal in southern Alberta.

4. Potential Solutions

If water transfers, or any form of water trading, is to be an effective instrument of water governance in southern Alberta, water rights must become more fungible across the definition (type of right) and transferability characteristics. This section draws on the work and institutional design in Australia and Colorado to offer possible mechanisms to make rights more fungible in the SSRB.

4.1.Sharing Scarcity

Similar to western Canada, water was deemed instrumental to irrigation and economic development in Australia (Commission, 2011). Riparian rights were abolished in favour of a system where water was vested in the state and the state allocated volumetric water licenses or entitlements, appurtenant to land (Tisdell, 2014). Due to the over-allocation of water resources and the subsequent environmental degradation, various states within the MDB instituted a moratorium on the issuance of new water entitlements (Tisdell, 2014; Wheeler et al., 2014). In 1986-87 formal water trades were introduced to reallocate water among users in an efficient manner (Lin Crase et al., 2004; Wheeler et al., 2014; M. D. Young, 2015).

Australia has undertaken an iterative and incremental approach to the development of its water market. After water trades were introduced, water entitlements were unbundled from the land and subsequently unbundled into rights to access water and separate water use rights (Commission, 2011; L. Crase et al., 2003; Lin Crase et al., 2004; Wheeler et al., 2014; M. D. Young, 2015). Unbundling is the process by which a property right is separated into separate instruments, each designed to pursue a separate target (M. Young & McColl, 2005). Scholars

assert that unbundling makes property rights more secure and facilitates water transfers (Grafton et al., 2012; M. D. Young, 2014; M. Young & McColl, 2005). In addition to unbundling water rights, Australia ceased to define rights in absolute volumetric terms and instead defined water rights as unit shares of the annual water availability (Commission, 2011).

Defining water rights as entitlement shares addresses multiple fungibility characteristics.

Primarily, water rights are defined in a homogenous way and all rights have the same rate of certainty with respect to climate. All rights are proportionately reduced during water shortages, eliminating the process of curtailing some rights as opposed to others. Defining water rights as entitlement shares also facilitates transfers because rights are relatively homogenous and can be transferred as opposed to several siloed water rights. Defining water rights in this manner potentially facilitates the trading of water shares in the future. A specific water share is secure (certainty characteristic) and a prospective buyer can address any potential water shortage issues by purchasing shares for a future date. Australia's approach to facilitating water transfers involved an incremental overhaul of their allocation regime. It must be noted that droughts and the resultant environmental degradation were major factors in the late 20th and early 21st century in Australia's water policy reform (Commission, 2011; Tisdell, 2014). Southern Alberta conversely experiences droughts intermittently and at times experiences flooding as it did in 2015 (Heinmiller, 2016). Adopting a similar approach in southern Alberta will require overhauling FITFIR. Given the layered approach to water governance reform in southern Alberta, an overhaul of the prior allocation regime would represent a radically different approach, to both the history of water governance and to the policy change process already undertaken.

In Colorado's CBT basin, water rights are also proportional shares (Carey and Sunding, 2001). Unlike the MDB and SSRB, these water rights are not the primary sources of water for right holders. They are supplemental (Carey and Sunding, 2001). The ease with which these shares are traded further illustrate the benefit to homogenizing water rights by defining them as proportionate shares across a basin. However, the institutional origin of the CBT water share system is radically different from both the MDB and SSRB where water rights were conceived as a supplemental source as opposed to a primary one. However, the experience of the CBT basin provides one insight in how to utilize stored water resources or other supplemental water resources in the SSRB.

4.2. Consumptive Water Use

Both the prior appropriation regime in the American West and the prior allocation regime in southern Alberta define water rights and licenses in terms of a volume of water to be diverted by a user (Boone et al., 2018; Percy, 1977). However, in an institutional environment where instream objectives and existing users must be respected, water transfers operate on the basis of the amount of water consumed (Squillace, 2012). Any prospective transfer can potentially impact third parties because the new user of water may consume more water than the previous user even if the amount specified for diversion remains unchanged (Squillace, 2012). However, defining water rights in this manner may be administratively burdensome and may be a large undertaking for the state (Squillace, 2012). Water rights holders may object to the state measuring their consumptive water use if they feel the volumes they have been historically granted could be curtailed. Water users who have conserved water with a smaller water right (in terms of volume)

must not be punished by any redefinition of water rights to garner their support. To avoid this scenario, these water users should not have their rights reduced. Australia reduced irrigator water rights based on historical consumption patterns in the 1970s without compensation leading to widespread dissatisfaction from irrigators (Commission, 2011). Defining the consumptive portion of water rights does not necessarily entail a reduction or restriction on the rights of water users, but it may require political capital to ensure the requisite buy-in from rights holders. However, redefining water rights to incorporate consumptive use patterns will help make licenses more transferable and allow senior license holders to maintain their priority status within the water allocation system.

In addition to transferability, defining the consumptive volumes of water rights helps clarify water use within a basin. How water is used affects the fungibility of water rights. Codifying the proportion of water that has been historically used by rights holders confers a degree of certainty with respect to the expectations of future water use and potential impacts on downstream water users, third parties or instream objectives. If the process of defining consumptive water use is implemented correctly, historical water use patterns will be maintained, and consumptive water use provisions will act as an additional institutional layer to facilitate an existing water license transfer system in southern Alberta.

5. Conclusion

Southern Alberta's water rights have several characteristics that make them non-fungible. One such characteristic is the transferability of these rights which directly impacts the water transfer system. The various water rights within southern Alberta are siloed, limiting their transferability.

As such, the new institutional layers of the water allocation regime are limited in their ability to change the policy orientation of water governance in southern Alberta. Addressing the fungibility criteria of water rights is a necessary condition to reduce the transaction costs of transfers and ensure water transfers are more than just a niche policy instrument. The experiences of Australia and Colorado illustrate the importance of addressing fungibility in an institutional structure where water markets exist. Following Australia's lead and overhauling FITFIR is not in line with the incrementalist approach already adopted within southern Alberta's water policy subsystem. Water rights in the SSRB are not supplemental like they are for the CBT in Colorado. The influence of the developmentalist coalition, and the existing infrastructure, have already attenuated calls for radical shifts in water governance in the region. While redefining water rights to include consumptive use patterns may be administratively burdensome and unpopular, the process will not necessarily impact historical water use patterns. Indeed, consumptive use definitions can provide accurate information on what these use patterns are. Defining water rights in this manner will make them more certain and provide clarity as to how much of a water license's volume is transferable.

If the lack of fungibility within southern Alberta's water allocation regime is not addressed, water license transfers and the water market will be limited. A sustained period of drought may change this situation, either by increasing demand for water or increasing demand for change. The use of stored water to allow water users to carry over their water allocation to the following year may help address some issues. Stored water provides more certainty and provides the flexibility to facilitate more creative trade options. Potential trades of stored water across different years allows water users to trade for guaranteed water allocations. These allocations can

be for specified times, which can attenuate fungibility concerns with respect to the timing characteristic. Stored water in the SSRB is not considered part of the natural flow (Rood, 2010) and is thus not subject to the priority system. This conception of stored water also provides an opportunity to allocate water in a manner that addresses pressing shortage concerns or institute a proportional sharing mechanism similar to the one used in the CBT. Even though CBT water is considered supplemental, the use of a proportional share allocation mechanism ensures those rights are fungible and easily transferable between users as shown in both Australia and Colorado. A similar mechanism for stored water in the sub-basins of the SSRB will ensure stored water allocations are fungible and may provide a degree of flexibility to the existing allocation regime.

The impact of a more fungible water rights system on the environment is an open question. If the environment is provided with a share of annual allocations the environment will clearly benefit. Defining consumptive water use amounts will prevent water users from increasing basin-wide water withdrawals in the pursuit of water transfers, which will prevent environmental degradation. Stored water can also ensure the timing of environmental flows is addressed. However, a more fungible water rights system on its own may not be sufficient. After making their water rights regime more fungible, the Australian government entered the water market and purchased water entitlements on behalf of the environment. The Alberta government outlined water conservation objectives in the SSRB after introducing a water market. These examples illustrate the active role the Alberta government has to play to ensure the environment receives adequate water quantity and quality – irrespective of the fungibility of water rights within an allocation regime.

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3. Allocating Water in Southern Alberta: A Quadratic Programming Model

1. Introduction

This chapter develops an optimization model for water allocation in the South Saskatchewan Basin (SSRB) of Alberta. Using the AQUARIUS modeling program, the annual value of water allocations in the SSRB are optimized over a 12-month horizon. The chapter depicts the current water allocation within the SSRB. This starting point is crucial as it is the standard of reference from which efficiency gains are measured. By reallocating water to where its marginal use is highest, this paper reveals potential efficiency gains in water use and arms policy makers with the means to anticipate the impacts of climate or alternate allocation policies and explore potential solutions such as the reallocation of water. The main contribution of this chapter is to show the economic impacts of changes in water supply and demand in a water basin with competing water uses. The chapter also simulates the impact of assigning economic value to instream protection areas on water allocations to municipal and agricultural areas.

Hydro-economic models represent a framework for integrating hydrologic, environmental and economic aspects of water resource systems on a regional scale (Harou et al., 2009). These modeling techniques have been applied to water allocation considerably in the recent past. Bielsa and Duarte (2001) developed an economic model for allocating water between two competing sectors, namely irrigation and hydropower in northeastern Spain. Similarly, Reca et al. (2001) developed an economic optimization model for water resource planning in deficit irrigation systems in southern Spain. A linear programming optimization model for analyzing seasonal allocations of irrigation water was introduced by Salman et al. (2001) whereas Wardlaw and Bhaktikul (2001) also used an optimization approach based on genetic algorithms for real time

allocation of irrigation water supplies. There have been computational models developed for the SSRB (Cutlac & Horbulyk, 2010; Mahan et al., 2002). Cutlac and Horbulyk (2010) developed a model with competing water demands to examine the impact of alternative allocations in the SSRB. Mahan et al. (2002) showed that water reallocation away from irrigation could lead to small efficiency gains in the SSRB, especially under drought conditions. Weber and Cutlac (2014) explored the difference between a prior allocation system and a system where water was distributed proportionally in the SSRB.

This chapter uses the AQUARIUS modeling program to simulate water use across different sectors. The results indicate that economic benefits from water use can increase through reallocation of water from agricultural to municipal users. The results also indicate that there are sufficient water resources over a 12-month horizon to satisfy the water demands of different sectors and satisfy minimum instream requirements under most of the scenarios considered. Section two examines how water is currently allocated in the SSRB. Section three introduces the optimization problem and how some of the institutional arrangements in the SSRB are represented in the model. The results of the optimization problem, as well as alternate simulations are discussed in Section four briefly followed by recommendations on how to allocate water in the face of impending climate change.

2. The Current Water Allocation in the SSRB

The SSRB of Alberta is comprised of the Red Deer, Bow, Oldman and South Saskatchewan sub-basins. Its total drainage area is 112,800 km² and its median annual flow is 8,842 MCM² (Alberta Environment, 2016). Annual precipitation in the basin varies spatially and is between 200-500 mm. About 70% of the annual runoff in the basin is supplied from the Rocky Mountains and the foothills and most of the surface water flow is supplied by the spring snowmelt (Tanzeeba & Gan, 2011). The total water available for allocation in the SSRB is constrained by the Master Agreement on Apportionment (Weber & Cutlac, 2014). Under the agreement, Alberta must pass 50% of the natural flow to Saskatchewan in a given year.

Currently, 76% of water withdrawals in the SSRB are for irrigation purposes (Bennett et al., 2017). The SSRB's climate is semi-arid and 86.5% of agricultural production is reliant on surface water resources (Tanzeeba & Gan, 2011). Irrigation demand increases in dry years, intensifying low flow scarcity issues. Some climate models have predicted reduced streamflow in the SSRB by the 2080s, and have shown that the 20th century was abnormally wet compared to the historical record (Matthews & Schmidt, 2014). Water demand in the SSRB is expected to increase as the 21st century progresses. This increase is largely driven by a projected population increase – to 2.5 million in 2030 and over 3 million in 2046 (1.65 million in 2006) (Bjornlund et al., 2014; Zuo et al., 2015). Water demand for the non-irrigation sector could increase by 35-67% by 2021 and by 53-136% in 2046 (Zuo et al., 2015). The projected increase in population will increase the public good payoffs derived from instream flows. Currently, the public derives some

² Million Cubic Meters. 1 MCM = 1,000,000 cubic meters

value from the existence of instream or environmental flows and an increase in population implies an increase in this public value component of existing instream flows.

Since the signing of the 1894 *North West Irrigation Act*, water has been allocated using the prior allocation regime (Pentney & Ohrn, 2008). During water shortages, water is progressively rationed by priority of license and withdrawals by junior license holders may be curtailed (Libecap, 2011). Under the prior allocation regime, priority is determined by the date of application for a license (Percy, 1977). Alberta revised its water allocation regime through the 1999 *Water Act*. While the *Water Act* preserved the prior allocation regime, it introduced voluntary water transfers between water users – a harbinger of a water market. These water transfers, were part of the transition to a more demand-oriented water governance regime in the SSRB (Heinmiller, 2016). There have been 203 permanent water license transfers as of May 2017 (Bennett et al., 2017).

3. The SSRB Water Allocation Model

AQUARIUS is a nonlinear, generalized water resource decision support system used to optimize regional water use and simulate alternative water allocation scenarios (Diaz et al., 2000).

AQUARIUS uses an object-oriented programming language. Using AQUARIUS, the SSRB was represented as a network of interconnected supply and demand nodes. The network included both physical and economic data in a spatially distributed setting (Figure 3). Figure 3 illustrates a portion of the network of nodes used to depict the SSRB. The full network, including the Bow and South Saskatchewan sub-basins are depicted in the appendix. Nodes labelled inflow represent inflows from headwater catchments. Nodes labelled ID represent an amalgamation of

irrigation districts in the southern portion of the Oldman sub-basin. IP1 and IP2 are instream protection zones in the Red Deer sub-basin.

Figure 3: Portion of SSRB as depicted in AQUARIUS

AQUARIUS allows for the development of a water allocation model designed to maximize the economic benefits to water use. AQUARIUS achieves this objective by reallocating water among different users specified in the model. Economic value is assigned to different water uses and these values vary according to location, seasonal factors and the quantity of water each user has. Quantitative data describes the physical characteristics of these demand and supply nodes, including the spatial relationships among upstream uses, return flows and downstream outcomes. Economic data describes the demand curves and marginal benefit for allocations of water to specific uses (Cutlac & Horbulyk, 2010). How the user interface allows physical and quantitative data to be added into the model architecture is depicted in the appendix. The model uses a monthly time step to optimize the benefits derived in a single year. AQUARIUS reallocates

water to users with a higher marginal valuation for water in order to maximize total economic benefits in the basin.

The flow balance at each node in the SSRB network is described by (Mullick et al., 2013):

$$Flow_{d/s,t} = Flow_{u/s,t} - withdrawal_t - \Delta conveyance\ loss_t \quad (1)$$

where $\Delta conveyance\ loss_t$ is the adjustment for any conveyance loss or gain in flow from an upstream point to a downstream point for a monthly time period t . This quantity is calculated by subtracting the upstream flow from the downstream flow on a monthly basis. The flow balance of the entire network, for a monthly time period, can be described as:

$$Sask_{inflow} = Inflow_{SSRB} - Withdrawals_{SSRB} - \Delta conveyance\ loss_t \quad (2)$$

Several constraints are imposed on the optimizations process. These constraints include limits on storage capacity in reservoirs, lower-bound quantity constraints on instream protection (IP1 and IP2) and the apportionment requirement with Saskatchewan ensuring at least 50% of inflows to the SSRB flow downstream to Saskatchewan. The top portion of the network in Figure 3 represents the Red Deer sub-basin while the bottom portion represents the Oldman sub-basin with three irrigation districts (IDs). The combined outflow after the confluence to the right of IP2 must equal at least 50% of all inflows into the SSRB:

$$Confluence\ (IP2 + South\ Saskatchewan) \geq \frac{Inflows}{2} \quad (3)$$

Storage reservoirs are depicted in AQUARIUS to transform streamflows into a series of releases that correspond with seasonal water demands in the SSRB. During the optimization process, a constraint is applied to ensure that the storage at the end of any time period did not fall below a reservoir's minimum active capacity (Diaz et al., 2000):

$$S \geq S_{min} \quad (4)$$

The spatial representation of the SSRB, which delineated the four sub-basins, includes demand nodes denoting municipal and agricultural users, a hydropower plant, reservoirs and is partially presented in Figure 3. The monthly inflows for the headwater catchments in the model are determined using the Water Survey of Canada (Environment and Natural Resources Canada, 2014). Only surface water sources are considered in this modeling exercise. The use of groundwater in the SSRB is not significant (Cutlac & Horbulyk, 2010) and this dissertation is primarily focused with the allocation of surface water resources. Four municipalities are depicted in the model: Red Deer, Calgary, Lethbridge and Medicine Hat. The 2014 Municipal water use report from Environment Canada is used to input data on water use in each city. The 13 irrigation districts in the SSRB are amalgamated into seven districts in the model and data on their diversions and return flows is derived from the Alberta Agriculture and Forestry annual report on irrigation water use (Alberta Agriculture and Forestry, 2016).

The objective function in this study maximizes the total economic benefits from alternate water uses over a one-year period. The objective function maximizes the sum of economic benefits from different uses by combining individual benefit functions, B , into a total benefit function, TB , that reflects all water uses u in the basin and all time *periods* i . The objective is to maximize the total benefit function TB in \$ (Diaz et al., 2000):

$$\max_x TB = \sum_{i=1}^t \sum_{u=1}^n B_u^i \quad (5)$$

where X denotes the set of control variables, n is the number of water uses in the basin, and t the number of time periods. Costs associated with the construction of canals or operation of municipal systems are not considered in the model. Individual benefit functions are represented

by Marshallian demand curves where income effects are assumed constant across different water uses (Willig, 1976). Marshallian demand curves closely approximate their Hicksian equivalents when income effects are small (Willig, 1976). Income effects for water are assumed to be small as water comprises a small portion of an individual's total purchases (Diaz et al., 2000).

This objective function (5) maximizes total benefits by reallocating water to where its marginal value is highest, until the difference in marginal value of water among different water uses is zero. The solution in AQUARIUS reduces the objective function to a quadratic form where all the constraints are linear (Diaz et al., 2000). A quadratic function closely approximates the objective function defined in (5) (Diaz et al., 2000).

AQUARIUS approximates the objective function using Taylor series expansion and then solves the problem as a quadratic programming (QP) problem (Diaz et al., 2000). AQUARIUS first finds an initial feasible solution, x_0 , and carries out a Taylor series expansion on the objective function around the given initial solution (Diaz et al., 2000). The general Taylor series expansion is (Diaz et al., 2000):

$$f(x) \approx f(x^0) + \nabla f(x^0)^T \partial x + \frac{1}{2} \partial x^T H(x^0) \partial x \quad (6)$$

where ∂x is the increment vector and $\nabla f(x_0)$ is the gradient vector of $f(x)$, measured at the initial feasible solution. The term $H(x_0)$ denotes the Hessian matrix, whose elements are also evaluated at the initial feasible solution (Diaz et al., 2000).

During the optimization process, equation (5) converts to the standard form of a quadratic programming problem, as defined by (Diaz et al., 2000, 2005):

$$\frac{Max}{x} [f(x) = w + c^T x + \frac{1}{2} x^T M x] \quad (7)$$

This quadratic problem is subject to the following linear constraint (Diaz et al., 2000):

$$g(x) = Ax \geq r \text{ where } x \geq 0 \quad (7.b)$$

where w is a scalar, and the c and r vectors have known components, A is the matrix of constraint coefficients, and M is a square matrix of dimension ($N \times N$). Once the equivalent c vector and M matrix have been explicitly defined, a standard QP code can be used to solve for the set of x values that maximizes the objective function (Diaz et al., 2000). The optimal solution is only true for the approximated objective function in equation (5). A succession of these approximations is performed until the solution of the quadratic programming problem is optimized (Diaz et al., 2005).

Economic efficiency is maximized when the sum of net benefits from various outputs is as high as possible given the physical constraints of a system, with benefits expressed by willingness to pay (Young & Gray, 1972). When water is allocated in the model architecture without any volumetric fees by the users, all the values for a given allocation can be characterized as consumer surplus. Water consumption for municipal areas is derived from per person consumption data and estimates. It is assumed that the raw water charges are the same for all uses within municipal areas. These charges are used as estimates of user's willingness to pay for current volumes. In the case of irrigation districts, consumption figures and charges are determined from the annual irrigation diversions, assessment roll acreages and annual water rates. It is assumed that irrigation districts comprise all agricultural users in this model. This paper assumes, the willingness to pay for a particular water use is independent of the willingness to pay for other water uses.

3.1.Economic Demand and Return Flows

Consumptive and non-consumptive water demands are modeled. Consumptive water demands are aggregated into seven irrigation districts and four municipal areas. Non-consumptive water demands are represented by storage reservoirs a hydropower plant and instream protection zones. Consumptive and non-consumptive water demands are represented using inverse demand functions while instream protection zones are depicted as lower-bound constraints. Inverse demand curves represent the marginal value of water (Diaz et al., 2000; Young & Gray, 1972). Demand prices for water represent a consumer's willingness to pay for varying quantities of water (Young & Gray, 1972). Water demand is shown in exponential form by the inverse demand function (Diaz et al., 2005):

$$P = aexp^{Q/b} \tag{8}$$

where P represents the unit price or marginal willingness to pay for water and Q represents the absolute value for monthly water demand. This functional form is the default specification in AQUARIUS (Figure 4).

Figure 4: Water Demand curve for Calgary in model

Defining water demand in exponential form implies that the demand curve intersects the vertical axis. This intersection represents the choke price of water for a specific use – the price at which consumption ceases in favor of an alternative (Cutlac & Horbulyk, 2010). These exponential demand curves can be calibrated in AQUARIUS using the choke price and another price-quantity pair. To calibrate these monthly demand curves, choke prices for irrigation and urban water users are inferred from Cutlac and Horbulyk (2010). Water prices for volumes for urban users are derived from monthly consumption charges in 2019. These charges were \$1.52/m³ in Calgary, \$1.27/m³ in Lethbridge, \$1.52/m³ in Red Deer and \$1.09/m³ in Medicine Hat. Water charges for irrigation ranged from \$0.02/m³ to \$0.032/m³.

AQUARIUS fits exponential inverse demand curves based on economic information provided (Diaz et al., 2000). If two price-quantity pairs are known, (p₁, q₁) where the quantity demanded approaches zero and (p₂, q₂), AQUARIUS can derive the parameters *a* and *b* in equation 8. The inverse demand function at (p₁, q₁) is (Diaz et al., 2000):

$$P1 = a \exp\left(-\frac{Q1}{b}\right) \quad (9)$$

and the inverse demand function at (p2, q2) is (Diaz et al., 2000):

$$P2 = a \exp\left(-\frac{Q2}{b}\right) \quad (9b)$$

For the two paired values, there is only one exponential inverse demand curve as shown in equation 8 that will assume the exact values $f(Q1)$ and $f(Q2)$ (Diaz et al., 2000). Substituting equation 9 into equation 9.b provides the following result (Diaz et al., 2000):

$$a = \frac{P1}{\exp\left(\frac{\ln\left(\frac{P1}{P2}\right)}{1-Q2/Q1}\right)} \quad \text{for } Q1 > 0 \quad (10)$$

$$b = \frac{Q2-Q1}{\ln\left(\frac{P1}{P2}\right)} \quad \text{for } Q1 > 0 \quad (10b)$$

At the choke price, the coefficients a and b are given by (Diaz et al., 2000):

$$a = P1 \quad \text{for } Q1 = 0 \quad (11)$$

$$b = \frac{Q2}{\ln\left(\frac{P1}{P2}\right)} \quad \text{for } Q1 = 0 \quad (11b)$$

Return flows in the model are computed as a fixed percent of the flow allocated and specified in AQUARIUS. Return flows are made fully available downstream during the same time interval of simulation. The return flow in each node is indicated by (Diaz et al., 2005):

$$\text{Return Flows} = rX \quad (12)$$

where r is the coefficient of return flow which is assumed constant throughout the year (Diaz et al., 2000). Return flow coefficients for irrigation districts are derived from their annual reports

and range from 0.15-0.3. Return flow coefficients for urban users are 0.7 and are derived from the 2014 Municipal Water Use Report.

3.2. Institutional Representation

Accurately depicting the institutional arrangements in the SSRB is equally as important as depicting the spatial components of the basin and user water demands. The Master Agreement on Apportionment is an interprovincial agreement on water sharing in the Saskatchewan-Nelson River Basin stipulating that one half of inflows in the SSRB in Alberta must pass downstream to the province of Saskatchewan. This agreement is represented in the model by a rigid, lower bound constraint in equation (3) requiring at least 50% of all inflows to flow into Saskatchewan. This apportionment agreement is for surface water, and limits Alberta's water consumption in the entire SSRB on an annual basis.

A key institutional feature of water allocation in Alberta is the prior allocation regime (Pentney & Ohrn, 2008). Prior allocation is an institutional constraint which prevents the reallocation of water to higher valued uses (Bretsen & Hill, 2009; Cutlac & Horbulyk, 2010). Prior allocation is depicted in AQUARIUS as a constrained optimization which results in a suboptimal allocation. To depict the current institutional environment as a constrained optimum, quantity constraints are imposed to prevent AQUARIUS from reallocating water away from some lower valued water users (irrigation). Once the current allocation is depicted, the quantity constraints preventing water allocation to higher valued uses are removed to simulate an optimized base case. This optimized base case adhered to operational storage requirements and the apportionment agreement with Saskatchewan. This approach shows how much economic value

could be gained by allocating to users with higher marginal valuations. This optimized base case is subsequently compared to other scenarios where water demand and supply are altered.

Initially instream protection zones are defined without any benefit functions due to the difficulty in estimating the value of water to the environment. Consistent with past modeling studies, environmental demands are specified as lower-bound constraints and are not treated as a source of value or benefit (Cutlac & Horbulyk, 2010; Diaz et al., 2000; Mahan et al., 2002):

$$flow\ IP_n \geq minENVR_n \quad (11)$$

where IP represents one of the six instream protection zones depicted in the model network (see appendix for full figure) and *minENVR* represents the environmental flow levels established by the Alberta Environment and Alberta Sustainable Resource Development at each sub-basin (2011). These levels varied at each instream protection zone. There are two instream protection zones in each of the Bow, Oldman and Red Deer sub-basins. In the Bow sub-basin 75% of flows needed to flow through one protection zone while at least 45% of the sub-basin's flows had to flow through the second protection zone. These figures were 65% and 75% in the Oldman sub-basin and 80% and 75% in the Red Deer sub-basin, respectively.

4. Results and Discussion

The optimization procedure examines the most efficient allocation of water in the SSRB over a 12-month period under different scenarios. The current allocation of water in the SSRB is compared to the optimized base case, an increased water demand scenario, a reduced streamflow scenario and a scenario where instream protection zones have economic benefit functions.

In the increased water demand scenario, water demands for consumptive users are increased in line with the projections of the SSRB Water Supply and Steering Committee. These projected water demands are incorporated into the corresponding sub-basins in the AQUARIUS model. All municipal and agricultural water demands in each sub-basin increase to correspond with projections provided by the SSRB Water Supply and Steering Committee. Given the water demand functions of each water user, the vertical intercepts are held constant and each user's monthly valuation of a given volume of water is increased by the SSRB Water Supply and Steering Committee Projections. The constraints are unchanged from the optimized base case.

The 20th century was abnormally wet compared to the historical climate record in the SSRB (Schmidt, 2014). Some climate projections predict an exacerbation of droughts and reduced streamflows. Indeed, some studies predict streamflow reductions of up to 26%, 41% and 54% in the Oldman, Bow and Red Deer basins respectively (Tanzeeba & Gan, 2011). These reductions could lead to water shortages in the SSRB and will undoubtedly impact the water allocation in the region. To simulate these streamflow reductions, the $Inflow_{SSRB}$ term in eq. 2 is reduced according to streamflow projections.

AQUARIUS allows for the specification of inverse demand curves for instream protection areas. These demand curves can either be specified as constant, horizontal demand curves or as linear, declining demand curves. Declining linear inverse curves are specified for the six instream protection zones in this scenario. Seasonal water requirements for instream water demand are determined using the *Water for Life* report establishing environment flows for healthy aquatic

systems (Alberta, 2011). The apportionment requirement remains as a lower-bound constraint when instream protection areas are modeled with a price function.

Currently, 7373.14 MCM of water flows into the SSRB from headwater catchments. Of these inflows, a minimum of 3687.07 MCM must flow downstream to Saskatchewan. The current water allocation to municipal and agricultural users, according to their annual water use reports are 216.02 MCM and 2338.03 MCM respectively (Table 3). The economic benefits from the current allocation are derived from a constrained optimization, as described previously.

Agricultural and municipal water use accounts for a large share of the economic benefits from water use with 57% and 42% of the benefits respectively. The shares from hydropower is relatively small in comparison. Annual hydropower generation in the model is assumed to be 1,914,200 MWh to be delivered at \$68/MWh. The price of 68MWh is the cap the government of Alberta implemented for hydropower prices from June 2017 to May 2021 (*Electricity price cap*, 2019).

4.1. Alternate Allocations

The results of the three simulated scenarios are presented in Table 3. The results include the volume of water allocated to each water sector and the economic benefits derived from each sector. In essence, the changes in total economic benefits between each scenario is depicted in Table 3. In Table 3, economic benefits and the volume of allocations to each sector have been aggregated over a 12-month period. In the optimized base case scenario, total economic benefits in the SSRB increase from \$904.1 to \$948.9 million. Return flows from agricultural and urban uses are part of the water resources that are reallocated by the model. Economic benefits from

hydropower generation are reduced from \$73.9 million to \$34.5 million as are the annual allocations to hydropower generation (Table 3).

The economic benefits derived from agricultural and municipal water uses, in the optimized base case, are \$472.95 million and \$441.44 million respectively. While the share of economic benefits from agricultural and municipal water use is similar in the optimized base case, agricultural users require over three times the water as municipal users. The overall impact of removing the quantity constraints in the base case scenario is an increase of total economic benefits in the SSRB, an increase in allocations to municipal water users and a reduction of water allocations to agricultural users. The distribution of water allocations between the four municipal users is not equal under the optimized base case. Calgary, receives 74% of all municipal water allocations under the base case scenario while Red Deer, receives 8% of these municipal allocations. However, Calgary's population is over ten times Red Deer's population meaning on a per capita basis, more water is allocated to Red Deer than Calgary under the base case scenario.

Table 3: Results from Alternate Allocations

Model Depiction	Urban Water Allocation (MCM)	Economic Benefits of Urban water use (millions)	Agricultural Water Allocation (MCM)	Economic Benefits of Agricultural water use (millions)	Hydroelectric Water Allocations (MCM)	Hydro Benefits (millions)	Reservoir Water Storage (MCM)	Instream Flows (MCM)	Total economic Benefits (\$Millions)
Current Allocation	216.02	\$321.1	2338.03	\$509.2	2462.3	\$73.9	3693.4	5326	\$904.1
Optimized Base Case (unconstrained optimization)	457.4	\$441.44	1418.18	\$472.95	1504.1	\$34.5	3693.8	6151.4	\$948.9
Reduced Streamflow	428.7	\$429.1	1352.3	\$389.1	1492.4	\$33.0	1873.7	4432.1	\$851.2
Increased Water Demand	687.0	\$670.95	1841.0	\$483.3	1631.4	\$35.1	1827	6208.7	\$1189.3
Price for Instream protection	398.4	\$420.6	1138.1	\$321.2	1423.8	\$31.7	1812.6	6404.5	\$2050

Table 4 provides the SSRB Water Supply and Steering Committee's (2009) water demand projections for urban and agricultural water uses. Demand in each of the SSRB's four sub-basins is expected to rise by 2030.

Table 4:SSRB Water Supply and Steering Committee Water Demand projections (2009)³

Sub-basin	Projected Municipal demand increase	Projected agricultural demand increase
Red Deer	100%	-
Bow	54%	32%
Oldman	41%	19%
South Saskatchewan	39%	-

Increasing water demand results in municipal users receiving 687 MCM of water. This volume is 33% higher than in the base case scenario. Agricultural users see their allocations increase by 23% under the increased water demand scenario. The economic benefits for both municipal and agricultural users increase to \$670.95 and \$483.3 million respectively. The corresponding economic benefits to water use in municipal and agricultural areas increase by 34% and 2.3% respectively. The overall impact of increasing water demand is an increase in allocations, especially to municipal users and an increase of economic benefits for both municipal and agricultural users. These increased water demands are not inhibited by any of the rigid constraints in the model such as the apportionment agreement with Saskatchewan or reservoir storage requirements. Reservoir storage declines by more than 50% when the demand for water

³ In the AQUARIUS model architecture, there are no irrigation districts in the Red Deer or South Saskatchewan sub-basins

in agricultural and municipal sectors increases. The distribution of water allocations between municipal users, remains similar to the distribution under the base case scenario.

Under the reduced streamflow scenario, inflows to the Red Deer, Bow and Oldman sub-basins are reduced, and consumptive water demands are returned to the levels in the base case scenario. As such, this scenario examines the impacts of changes to water supply on the SSRB water resources. Reservoir storage declines in this scenario, as it did under the increased water demand scenario. Water allocations to municipal and agricultural users declines slightly from the base case. The resulting decline to total economic benefits in the SSRB is slight due to the use of stored water to augment a declining water supply. This chapter optimizes water use over a 12-month optimization period. This optimization period significantly impacts how stored water is used within the model. In the case of water shortages, as shown in this scenario, stored water can be used to augment reduced inflows and satisfy consumptive water users. However, if a multi-year optimization period was used, stored water may be utilized differently.

This chapter also specifies a declining price function for the instream protection zones in the model architecture. To simulate a starting price for instream protection that is high enough to be binding at low water levels, instream protection water demands are specified horizontally at 0. These horizontal demand functions are iteratively increased until a binding price for instream protection is found. This price is subsequently used as a vertical intercept for declining inverse demand curves. AQUARIUS can simulate constant or linear demand curves for instream protection areas.

Price functions of instream protection zones are simulated under similar conditions as the base case scenario. Prices for environmental use or instream protection vary in the literature. In the US, choke prices for the environment were estimated to be between \$41 and \$53/acre-ft (Gibbons, 1986). These prices are equivalent to \$0.04/m³. The choke price simulated in this study is \$0.38/m³ as it is the price at which water allocation to instream protection zones is binding in the model architecture. The price elasticity of environmental water use also varies within the literature. This variation is partly because environmental water use or instream protection encompasses multiple environmental functions. For example, the price elasticity for protecting instream areas from eutrophication is estimated at -1.86 (Hökby & Söderqvist, 2003). This elasticity may differ from the price elasticity of maintaining wetland areas.

A linear, inverse demand curve with a slope of -2 is simulated for instream protection areas. This curve is a conservative estimate and attempts to simulate instream protection generally as opposed to a specific measure (eutrophication). With this demand curve, water to municipal users declines to 398.4 MCM. The decline in water allocations to agricultural areas is more pronounced, with 1,138.1 MCM allocated to these areas. The economic benefits to these areas are \$420.6 million and \$321.2 million respectively. Economic benefits basin-wide rise to \$2,0472.2 million from \$949.8 million in the base case. While this represents a significant increase in basin-wide economic benefits, it is not surprising considering six new water users (representing the six instream protection areas) are recognized as sources of economic value. If a more inelastic demand function is specified (steeper slope), less water would have been allocated to instream protection areas and more water would remain with municipal and agricultural users. To assess the sensitivity of these allocations to the elasticity of instream protection zones, a more

inelastic demand (slope of -1) is specified. Allocations to municipal and agricultural users is 400.1 MCM and 318.6 MCM respectively. When the price elasticity of instream protection is even more inelastic (slope of -0.5), the change in allocations is negligible. This analysis indicates that instream protection zones have the potential to impact water allocations to consumptive water users. This impact is sensitive to the price elasticity of instream protection zones up to a certain point. A more inelastic demand curve will impact allocations to agricultural and municipal water users. However, the difference in allocations between demand curves with a slope of -1 and a slope of -0.5 is negligible on water allocations.

4.2. Interpretation

With AQUARIUS, water use in a basin is optimized when the difference in marginal valuation between different users is zero (Diaz et al., 2000). AQUARIUS continually transfers water from lower valued uses to higher valued uses. In the simulated scenarios, the marginal valuation between different users is not equal. This result is because of the operational and institutional constraints imposed on the model. While the current allocation is presented as a constrained optimization to show the effects of the prior allocation regime, all simulated scenarios are subject to the apportionment agreement with Saskatchewan and reservoir storage limits. Due to these constraints, the model is not able to allocate water in a manner where the difference in marginal valuation between users is zero.

Another constraint in the modelling scenarios are the minimum levels of water allocation to six instream protection zones. Minimum instream constraints are binding in only the reduced streamflow scenario. When AQUARIUS attempts to optimize water use under this scenario, the

model fails to find an initial feasible solution where water demands, along with constraints for environmental water flows and the apportionment requirement are satisfied. To simulate the reduced streamflow scenario, the rigid constraint on instream protection zones is gradually relaxed. Minimum instream requirements are first reduced by 10% and then reduced proportionally to inflow reductions. This implies that acute water shortages will have an impact on the amount of water that can be allocated to instream protection zones – unless water demand decreases, or more storage is available. In the reduced streamflow scenario, stored water is used to augment the reduction in water supplies over a 12-month horizon. If a multi-year horizon is modelled with a prolonged water shortage, and stored water is not used as a short-term solution, water to instream protection zones could be reduced significantly.

When a pricing function is ascribed to instream protection areas, allocation to municipal and agricultural areas declines. However, one of the limitations of the AQUARIUS program is its ability to model only a constant or linear demand function for instream protection areas.

However, the model does simulate how ascribing a high, binding, price function for instream protection areas impacts other water users within the basin. The level of water allocation to instream protection areas in the model should be interpreted with caution. Once the demands of instream protection areas are satisfied, they still receive water as a result of return flows from consumptive users, which the model measures as a source of economic value.

Simulating a price for instream protection is an alternative to specifying lower-bound constraints for these areas within the model. Under the base case scenario, specifying minimum flow requirements for instream protection areas is not binding. However, specifying a price that is

binding reduces water allocation to both municipal and agricultural areas. This implies ascribing economic value to instream protection has the potential to reduce water allocations to consumptive users in an environment where water is allocated based on its marginal value.

Water resources in the SSRB have been described as over-allocated. Southern Alberta had a drought in 2015, but again, water market activity did not increase in any significant way as a result (Heinmiller, 2016). The term ‘over-allocation’ is used to describe instances where the volume of water held in licenses exceeds the volume of water in the reaches of the SSRB. This ‘over-allocation’ does not necessarily constitute a shortage of water. Only about 68% of water held in licenses is actually used annually (Bennett et al., 2017; Pentney & Ohrn, 2008). The results of these modelling scenarios show that ‘over-allocation’ of water in the SSRB could be a concern if water demands increase – as projected – or water shortages persist over prolonged periods. While storage reservoirs can augment water supplies to address these challenges in the model, their ability to address changes in water demand or supply over longer time horizons must be evaluated. If prolonged water shortages occur in the future, alternate methods of allocating water may need to be explored. Allocating water as proportional shares in times of acute scarcity may be one possible solution as shown in Chapter two in the case of Australia. Another potential solution is the promotion of a futures market for water licenses. The incorporation of such a market may allow certain water users to hedge against the risk of reduced allocations and provide compensation for water users who decide to sell licenses.

The optimized base case shows that total economic benefits can be increased if water is reallocated to users with higher marginal valuations for water. In the model results, this primarily

results in a reallocation of some water from agricultural users to municipal users. Indeed, in the base case, increased water demand and reduced streamflow scenarios, water allocations to agricultural areas are lower than the current allocation. Increased water allocations to municipal water users is consistent with previous modeling studies in the SSRB (Cutlac & Horbulyk, 2010; Mahan et al., 2002; Weber & Cutlac, 2014) and studies advocating for some reallocation of water from agricultural to urban uses due to the difference in marginal valuations (Bretsen & Hill, 2009). This chapter adds to previous studies by simulating a declining price function for instream protection areas. While the model limited the type of functions that could be ascribed, it was possible to simulate how water allocations to other uses could decline in the face of a pricing function for instream protection, if water was reallocated to where its marginal value was highest.

A removal of the prior allocation constraint in the model, results in costless reallocation of water in the subsequent scenarios. While some studies have interpreted the reallocation of water without such a constraint as analogous to a water market, it is important to note that the model occurs in an environment devoid of transaction costs and does not simulate an actual water market. The results do show that there is room to increase economic benefits through reallocation of water. Water license transfers are one mechanism by which this reallocation may take place, but not necessarily the only mechanism. Irrigation districts could lease water to cities through assignments and maintain their priority for example.

This modelling exercise assumes water use is fungible across different uses. As shown in Chapter two, water rights have seven dimensions of fungibility and water rights in southern

Alberta are not fungible across several of those dimensions. One of these dimensions is the transferability of water rights. Chapter two illustrates how water rights are siloed and cannot easily be transferred across institutional barriers. Water quality is also not a consideration in the modelling environment but could be a barrier to water reallocation. Institutional barriers to water reallocation also exist, as discussed in the previous chapter. The optimization procedure does not consider these institutional complexities, and as such the results, especially those pertaining to welfare improvement through reallocation, should be interpreted with the institutional barriers to reallocation in mind. Another barrier to water reallocation is the reluctance of irrigators to part with all or a portion of their water rights (Bjornlund et al., 2014; Rahimova et al., 2016).

Irrigation's value in the SSRB is not purely due to its economic value. Entire communities are dependent on the sector and the sector has amassed great political influence since the prior allocation regime was enacted in 1894. Indeed, this chapter shows that the irrigation sector is a large user of water in the SSRB despite the presence of other users with higher marginal valuations of water. The institutional arrangements ensure that irrigators (and other senior license holders) receive their allocations that in turn result in sub-optimal allocations. The reason these institutional arrangements persist is the political influence of irrigators, an influence that grew with the institutions that govern water use in the basin. The next chapter explores how water allocation is subsumed into the political structure of southern Alberta and sheds some light into the strategic interactions between users within the basin.

A key component of water reallocation in this modelling procedure is the return flows from withdrawals within the SSRB. The optimization procedure continually reallocates return flows to

satisfy consumptive water demands and minimum instream protection requirements. A reduction in return flows will reduce the volume of water that can be reallocated within the basin. These return flows can satisfy minimum instream requirements in the model, but their ability to be reused by either the environment or other consumptive water users is conditional on their quality. Future works should integrate water quality considerations into these hydro-economic modeling exercises.

5. Conclusion

The optimization results indicate there is potential to reallocate water more efficiently and increase the total benefits to water use in the SSRB. While water allocation results in an increase of economic benefits, the institutional arrangements and operational constraints modeled inevitably lead to a sub-optimal allocation of water. The scenarios in this chapter are for a 12-month horizon and the results indicate there are enough water resources in the SSRB to satisfy an increase in water demands from municipal and agricultural users within the basin. Future studies could optimize water use across longer time horizons and incorporate reservoir storage uncertainty. The results highlight the importance of reservoir releases to meet water demands in the increased demand and reduced streamflow scenarios. Future studies can assess how uncertainty with respect to the storage dimension can impact water allocation with fluctuating demand and supply scenarios. Future studies can also incorporate recreational water use and assess how changing demand or supply conditions impacts its valuation within the SSRB.

If extreme streamflow reduction projections do occur, water supplies will be insufficient to satisfy all consumptive water uses unless minimum instream requirements are relaxed. The

maximization of economic benefits to water use may not be a public policy concern of politicians or water users in the SSRB. Instead of efficiency, their objectives may revolve around a more equitable distribution of water resources or a distribution that is consistent with the growing importance of certain industries, or to ensure greater flexibility to mitigate intermittent shortages.

One crucial aspect of water allocation in the SSRB going forward is the role of cities. The cities and suburbs of southern Alberta have grown at some of the fastest rates in Canada during the 21st century. In this modeling exercise only four cities were depicted in the modeling architecture. Given the amount of urban and suburban areas in the SSRB and given the projections for increased water demand in municipal areas, the potential for welfare gains may be higher than actually depicted in this exercise with only four major cities. Another likely occurrence is an increase in the value of instream flows as the population of southern Alberta increases. The increase will be greatest for those aspects of instream flows that are public goods.

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4. The Political Incentives of Water Allocation in Southern Alberta

1. Introduction

This chapter explores the elements underpinning the primacy of irrigation in southern Alberta's water policy subsystem. It provides an explanation of the continual state support for irrigation, despite the presence of alternative, potentially more valuable water uses. This support persists despite strong popular opposition and despite political and climate related obstacles. Irrigation accounts for 75% of water consumption and withdrawals in southern Alberta (Bennett et al., 2017; Nicol et al., 2010). Despite studies asserting the presence of more valuable marginal uses of water, irrigation continues to dominate water use in southern Alberta. Irrigation has dominated water use in southern Alberta since the *Northwest Irrigation Act* was signed in 1894. It is a stable phenomenon. The primacy of irrigation has remained unaltered since the early 20th century. This primacy has become stable and is a fixture of water allocation in southern Alberta. It is institutionalized.

This chapter examines the water allocation regime in three ways. First, it explores irrigation's importance to the settlement objectives of the federal government of Canada in the late 19th century. Secondly, the incentives of both the state and irrigators are explored within this policy subsystem. In referring to the state, this chapter conflates the role of the federal and provincial governments. Through the use of an analytical model it is shown that cooperation between the state and irrigators, with respect to water policy, resembles a subgame perfect equilibrium. Once the underlying incentives are examined, how this equilibrium has persisted over time is explored by analysing the relationship between economic policy and politics.

Alberta's water was deemed essential for developing an agrarian society in the prairies, facilitating western settlement through irrigation and promoting Canadian sovereignty (Schmidt, 2014). The results of the analytical model show that irrigation's instrumentality to settlement is not the reason why the current allocation of water persists. Irrigation's importance to Alberta has declined over the course of the 20th century. In the 1920s irrigation accounted for over 50% of Alberta's total GDP (Heinmiller, 2016) and declined to 3.2% by the 1990s. In 2017, irrigation accounted for 1.7% of Alberta's total GDP (Heinmiller, 2016). In addition, Alberta has undergone a process of urbanization over the course of the 20th century. In 1951, 49% of the province lived in cities of 1,000 people or more (Alberta Land Institute, 2016). By the 1990s, this figure reached 80% (Alberta Land Institute, 2016). This urbanization reflects a declining percentage of people who are connected to and sympathize with agriculture and rural economic development in Alberta.

Despite these trends, irrigation accounts for the vast majority of water licenses held in southern Alberta. The argument developed asserts that the state supported irrigation initially to promote settlement. This approach rests on two components: the relationship between political and economic policy in the Prairies during the late 19th century and the importance of irrigation to settlement in southern Alberta and the Prairies more generally. The state provided irrigators with legislative and fiscal support. This support continued despite initial difficulties establishing irrigation in the prairies. Once the federal government's settlement objectives were fulfilled, the provincial government continued to support irrigation in order to secure electoral votes in southern Alberta. The regional concentration of irrigation makes its proponents the pivot in electoral politics within a first past the post electoral system.

Two models explaining the major phenomena of the 20th century in the water policy sub-system are developed. These models pay close attention to the narrative regarding the development of southern Alberta's water policy subsystem. The first model shows the mutual incentives of irrigators and the state from an economic perspective. The second model shows how the regional concentration of irrigation made irrigators a pivot politically. Their position as the pivot ensured their importance to electoral success for the governing party and their dominance of the water policy subsystem. As an analytic narrative focused on a unique event (Bates, 1998), these models are developed in the specific context of southern Alberta and offer two types of empirical tests. The first is based on the model's characterization of southern Alberta's political environment leading to particular results with respect to water policy. The second is the impact of exogenous events – namely climate – on the underlying equilibrium of water allocation in the region.

The next section provides a short narrative of the late 19th and early 20th century in southern Alberta's water policy subsystem and background on the development of irrigation. The following section develops a model of the incentives of irrigators and the state, both in the presence and absence of popular opposition to water projects favouring irrigation. The next section translates this model into a sequential game, and an empirical test of one of the model's central assertions is provided.

2. A Narrative of Events

There are 13 irrigation districts within southern Alberta and the licenses held between these districts accounts for 87% of the volume of total water licenses within the SSRB (Bennett et al., 2017). Prior to the establishment of irrigation in the prairies, settlers were engaged in dryland

farming and ranching activities. The federal government's objective was to attract individual settlers and farmers and encourage them to stay on the land and develop the land, to create greater traffic for the Canadian Pacific Railway (CPR) and to transport prairie farm products to the east (Hedges, 1939). Before the development of a large agrarian economy in southern Alberta, the dominant water users in the region were ranchers (Schmidt, 2011). These ranchers worried that government programs encouraging settlement would privatize land (Schmidt, 2011). Despite John Pallister stating in 1860 that southern Alberta was "the least valuable portion of the prairie country" the *Dominion Lands Act* (1872) was passed encouraging settlement in the prairies and opening the door to railway expansion in 1883 (Palliser & Blakiston, 1860). The *Dominion Lands Act* (1872) had parceled the continuous landscape of the prairies into 160-acre plots of land and encouraged settlement along the course taken by the CPR (Schmidt, 2011). The CPR was a large landholder in the prairies from its inception in 1881, when the federal government granted it a 25-million-acre land subsidy (Eagle, 1989).

The CPR was not required to accept lands which "consist in a material degree of land not fairly fit for settlement" (Eagle, 1989). Using this clause, the CPR made sure they received the best land available in the prairies. The settlement and development of the prairies was an important objective of the CPR as well. CPR president George Stephen (1881) stated that the CPR simply did not want to sell the land, but to settle it (Hedges, 1939). This objective could only be fulfilled through the development of irrigation. Without irrigation, agriculture in southern Alberta was not a sustainable endeavor. This reality established complementary incentives for irrigators and the government. The government needed irrigation to succeed to foster settlement and development, while irrigators needed irrigation to succeed to prosper and develop their lands. Western

settlement was so important to the government that they were initially afraid that the need for irrigation would discourage settlers by tipping them off to the semi-arid conditions that would greet them in southern Alberta (Schmidt, 2011).

Since the signing of the *Northwest Irrigation Act* in 1894, irrigation has been central to the federal government, and later, Alberta's provincial government. The objective of the *Northwest Irrigation Act* was to facilitate intensive agricultural production in the southern prairies by allowing prospective irrigators access to as much water as they could put to use (Heinmiller, 2016). Southern Alberta was acquired by the Canadian government in 1870 as part of the Northwest Territories. The task of occupying and settling this territory was also crucial to the federal government as a bulwark to any northward expansion of the American government (Schmidt, 2011). The CPR also wanted to add value to their land grants by constructing irrigation projects. To achieve this, the CPR required secure access to large quantities of water (Hedges, 1939).

The *Northwest Irrigation Act* introduced Alberta's prior allocation regime. This allocation mechanism is based on the priority principle – First in time, first in right (FITFIR) – and still persists currently. A priority list identifies older water licenses as “senior” and newer water licenses, with less priority as “junior”. Some of the oldest, most senior water licenses within Alberta are held among these 13 irrigation districts (Bennett et al., 2017). The primacy of irrigation has increased since the late 19th century. While the legal framework of the prior allocation regime favoured irrigators with seniority, irrigation was still a difficult and costly endeavor in southern Alberta. Irrigation districts were not economically viable in the western

part of North America (Bretsen & Hill, 2007) and needed government assistance (Klassen & Gilpin, 1999). Canada's federal government introduced the Prairie Farm Rehabilitation Act in 1935 to aid in the construction and maintenance of irrigation districts. The 1970s were a decade of unprecedented irrigation expansion in the SSRB (Heinmiller, 2016; Klassen & Gilpin, 1999). Alberta adopted a policy of acquiring and operating the headworks of the irrigation districts, deeming the operation of this infrastructure to be in the provincial interest. The province also expanded and refurbished the existing water infrastructure and conveyance systems for irrigation, while paying for 86% of the costs (Heinmiller 2016).

These historic developments show how irrigation's success was closely linked with state support. Irrigation districts and irrigators also possess considerable political influence within Alberta (Sproule et al., 2008). Irrigation is regionally concentrated in Alberta giving irrigators considerable influence in a single-member plural electoral system. From 1975 to 2012, the irrigation belt consistently returned PC MLAs to the Alberta legislature, giving them strong representation in the party that governed the province continuously from 1971 to 2015 (Heinmiller 2016). The extent of PC electoral dominance within southern Alberta is discussed later in this chapter.

The primacy of irrigation in the SSRB exhibits some path dependent features. Path dependence is a dynamic process involving positive feedback and increasing returns to scale which make it difficult to change course (Pierson, 2004). Existing institutions induce self-reinforcement and make reversals unattractive over time (Pierson, 2004). They can encourage actors to invest in specialized skills, deepen relationships with other individuals and organizations and develop

particular political identities (North, 1990; Pierson, 2004). These activities, in turn, increase the attractiveness of existing institutional arrangements relative to new arrangements (Pierson, 2004) and make existing structures self-reinforcing. Self-reinforcement involves increasing returns as each additional expenditure of resources generates a higher return than the one before it (North, 1990). In the context of water allocation, investment in irrigation and economic development becomes more beneficial the more the state invests in it. Alberta's adoption of the prior allocation regime and determination to keep water management in the public sphere to facilitate irrigation required the construction of an extensive network of dams, storage reservoirs and other conveyance structures. This complementarity illustrates how irrigation and water policy were linked at the outset in southern Alberta.

Southern Alberta's water allocation regime had problems as early as the 1920s (Percy, 1977). These problems arose because substantial water resources were allocated for irrigation and new socially important water uses were emerging, notably developing urban areas. Prior allocation did not provide a mechanism to transfer existing water rights to new, socially more valuable water uses (Percy, 1977). These problems were addressed through some statutory measures, whereby water could be transferred to water uses that were statutorily recognized as more valuable. These measures were at the discretion of the government who could cancel a statutorily inferior license in favour of one deemed more valuable (Percy, 1977). These provisions did mitigate the rigidity of the temporally based water allocation regime. However, their potential to reassign water licenses was strictly dependent on a set of statutory principles. These principles may have reflected the development and economic priorities of the early 20th century but may not reflect current priorities. The most common remedy to the need to assign

water to emerging users was through the development of new water supply projects (Percy, 1977).

These water supply projects allowed irrigation to expand in the SSRB throughout the 20th century. This expansion came with significant government investment, both federal and later provincial.

2.1. State Support of Irrigation

Initially, the state provided an appropriate legal framework for irrigation systems but did not provide financial capital. Even after irrigation districts were established in 1915, the federal and provincial governments did not initially provide funding for the construction of the requisite conveyance infrastructure. Similar to private forays into irrigation, the irrigation districts struggled and needed the assistance of the provincial government to remain viable (Klassen & Gilpin, 1999). Indeed, several were run as Crown corporations (Smith, 1978). The question is, why did the state finally decide to provide aid for irrigators?

The government's decision to provide financial capital and help construct irrigation systems was because of the transaction costs inherent in irrigation (Bretsen & Hill, 2007). Irrigation at a large scale requires an extensive network of dams, canals, storage reservoirs and other conveyance structures. Individual farms cannot construct and maintain these structures as the optimal farm size is different than the optimal size of the water delivery organization. The government was the only authority with the requisite capacity to construct and maintain the water infrastructure

needed for irrigation. Indeed, the replacement cost of Alberta's irrigation infrastructure is over \$4 billion, including over 1400 dams (Sproule-Jones et al., 2008).

The failure of early, private, irrigation endeavors was something the government could not accept. Irrigation needed to succeed in order for the government to credibly encourage Canadians to move west. Transaction costs were not the only barrier to the establishment and viability of large-scale irrigation in southern Alberta. The variability in the region's climate was another factor. In the 1930s, southern Alberta experienced a period of prolonged drought that lasted seven years from 1929-1936 (Francis & Ganzevoort, 1980). This drought brought both economic depression and terrible environmental effects associated with the dustbowl. Economically this period was a catastrophe for farmers as prices for wheat dropped to virtually nothing (Francis & Ganzevoort, 1980). By the mid 1930s, people were leaving the prairies (Francis & Ganzevoort, 1980). The failure of agriculture would have undermined the government's long standing efforts to foster an agrarian society in the region (Schmidt, 2011).

The PFRA was meant to give encouragement to farmers by addressing water and land management challenges related to agriculture (Klassen & Gilpin, 1999). The difficulty of establishing irrigation systems and the impacts of the depression and droughts in the 1930s exposed how essential government support was for irrigation in southern Alberta. The government's continued support and funding for irrigation revealed how important its establishment was to the overall objectives of the federal government. To understand this co-dependence on irrigation, the situation is depicted as a non-cooperative, sequential game. Game theory can identify and interpret the behaviour of parties in water allocation disputes and

describe how their strategic interactions result in the evolution of an allocation regime (Madani, 2010). Game theory can show how outcomes differ from the result of an optimization problem which assumes actors can cooperate and pursue the best basin-wide outcome rather than strategically trying to maximize their own preferences (Madani, 2010).

The first model analyzes the characteristics of the mutual cooperation equilibrium between irrigators and the government. In such equilibria, irrigators and the government cooperate – irrigators advocate for government support and the government provides the requisite funding for irrigation systems. Focus on this equilibrium is motivated by two considerations. First, continual support for irrigation by the state indicates that both irrigators and the state found irrigation mutually beneficial. Second, despite setbacks, such as the failure of early irrigation projects (Klassen & Gilpin, 1999), the drought and dustbowl in the 1930s (Francis & Ganzevoort, 1980), and the presence of other water uses requiring state support (Percy, 1977), the relationship between irrigators and the state persisted. This paper uses game theory to explore why this relationship persisted.

For simplicity, the analysis first examines the incentives of these two actors in the late 19th and early 20th century when irrigation was first being established. This analysis is then extended to the 1970s and the increased fiscal support for irrigation by the federal government. This approach reveals the distinct political and economic characteristics of irrigators and the state and enables the comparison of insights from this theoretical analysis with the historical evidence.

3. Modeling

There are two actors in this model – irrigators and the state. Each actor possesses a strategy combination – a complete listing of the choices that they will make at each point in every subgame. A strategy combination is a Nash equilibrium if no player can benefit from altering their choices, given the choices of others (Bates, 1998). A subgame perfect equilibrium includes the additional restriction requiring that in every subgame a player's action constitutes a best response to the actions taken by others in the subgame (Bates, 1998). The notion of subgame perfect equilibrium thus requires threats or promises to be credible. Players remain on the equilibrium path because it is a best response to the actions of other players. These credible threats will be discussed further in the second model.

Irrigators can choose to advocate for government support or not. Refusing to ask for or accept government support does not appear to be a credible option at first glance. However, in the late 19th century settlers moving west in both southern Alberta and the American West believed rain 'followed the plow' (Percy, 1977; Reisner, 1993). The ethic espoused in these regions was at odds with asking for and receiving government support (Reisner, 1993). When precipitation became scarcer the need for irrigation and subsequent government support became apparent. The state can choose to support irrigators or not. Supporting irrigators is tantamount to providing funding and allocating political and fiscal resources to irrigation at the expense of alternative water users and uses.

Irrigators' ability to garner state support for their projects is limited by their resources, consisting of political leverage and the ability to mobilize public opinion. Irrigators' calls for government

support date back to at least 1894. The South-Western Irrigation League of the North-West Territories was formed in 1894 in Calgary and sent a delegation to Ottawa, urging the government to pass the *Northwest Irrigation Act* (Heinmiller, 2016). In 1907, the Western Canada Irrigation Association was formed by farmers, businesses, railway companies and government agencies with an interest in irrigation. This organization spanned all four western provinces and was instrumental, through lobbying in the passage of the Irrigation Districts Act of 1915 (Heinmiller, 2016).

Indeed, without the *Northwest Irrigation Act*, non-riparian land would not have been developed and irrigation would not have been feasible. The entire enterprise was dependent on some government support, either legislative support, fiscal support or a combination of both. Irrigators will advocate for more support to ensure the viability of their enterprises and to reduce the costs associated with irrigation as long as the costs of irrigation exceed the political costs of advocating for state support. To examine how irrigation support can be replicated in a self-enforcing manner it is useful to begin by examining a political game between irrigators and the state (Figure 5).

Figure 5: The Political Game

The game depicted in Figure 5 unfolds simultaneously. The payoffs to irrigators and the state are presented in the last stage of this diagram. The question this game addresses is the extent to which the state will support irrigation. Irrigators have a decision of whether to:

- 1) Advocate for government support or;
- 2) Don't Advocate for government support.

The state in turn also has two choices:

- 1) To provide support for irrigation. Support may be legislative, fiscal or both;
- 2) Or to not provide support to irrigators.

R_i is the return or gross benefits that irrigators receive from irrigation and R_s is the return or gross benefit the state receives from irrigation. R_o is the return the state receives from alternative water uses and C is the cost of constructing irrigation systems. T is the transaction costs irrigators face when advocating for state support. R_s encompasses both tax revenues and more broadly the state achieving its objective of fostering settlement in southern Alberta.

Irrigators will advocate for state support as long as the transaction costs of advocating for state support are less than the actual costs of irrigation systems:

$$R_i - T < R_i - C$$

$$T < C$$

If irrigators advocate for state support and the state does not provide it, irrigators receive an outcome of $R_i - T - C$. This outcome is worse than not advocating for state support. For simplicity, it is assumed that the costs of irrigation are borne entirely by either the state or irrigators. As long as the costs of constructing and maintaining irrigation infrastructure exceed the costs of advocating for it, advocating for government support is a dominant strategy for irrigators. Since irrigators will always advocate for government support under such circumstances the analysis examines whether the state provides assistance or not.

The state does not provide assistance if $C + R_0 > R_s$. For the state to support irrigation the benefits must not only exceed the costs but must also exceed the forgone benefits of allocating resources to other users within southern Alberta. The gross payoffs for supporting irrigation to the state are $R_s - C$. The gross payoffs of not supporting irrigation are R_0 . For the state to support irrigation:

$$R_s - C > R_0$$

$$R_s > R_0 + C$$

where the benefits from irrigation to the state has to be more than the sum of the benefits of water to alternate water uses and the cost of irrigation. In the late 19th century, irrigation was essential for agricultural development and intensive settlement in the prairies. The federal government was also wary of northward expansion by the United States. Encouraging large scale

permanent settlement was the primary objective of the *Northwest Irrigation Act*. In this context, with a low population density and fears of northward expansion, irrigation was the most important water user for the state. As such, $R_s > C + R_o$ and the government supported irrigation.

One exogenous factor which affects this equilibrium is climate. Southern Alberta has a semi-arid and variable climate. The lack of consistent precipitation was one reason why irrigation was a necessary condition for agricultural development in the first place. The 1930s the prairie dustbowl and widespread environmental degradation called into question the viability of agriculture in the prairies (Francis & Ganzevoort, 1980). These climatic conditions temporarily increased the cost of irrigation in the region. Maintaining irrigation in the face of these environmental effects required additional investment.

In the model irrigators who needed government support before these events would continue to advocate for government support. Despite the increased costs associated with irrigation, the state continues to support the industry due to its initial settlement objectives. During the dustbowl, people were leaving their homesteads, a situation the state, which had invested in promoting settlement could not ignore. This situation led to the federal government stepping in with the Prairie Farm Rehabilitation Administration (PFRA) to preserve and improve the viability of agriculture in the region (Klassen & Gilpin, 1999). The PFRA identified irrigation as a priority area and directed massive sums of money towards irrigation development (Heinmiller, 2016). The model in Figure 5 confirms the historical narrative. When the costs of irrigation rise – due to external factors such as climate – irrigators need further support from the state. From the state's perspective, R_0 before settlement was negligible (this ignores the presence of the indigenous

peoples living in southern Alberta before settlement). As long as irrigation remained important to maintaining permanent settlement and development in the region during this time, the state continued to support it.

Mutual cooperation is indeed a subgame perfect equilibrium. Through backwards induction the model shows that the state will support irrigation because the payoffs are higher than not supporting irrigation ($R_s - C - R_0 > R_0 - R_i$). Irrigators will advocate for state support as long as C is greater than T . In other words, as long as the costs of irrigation exceed the costs of advocating for it (which is most likely the case) irrigators will always advocate for state support. The enactment of the *Northwest Irrigation Act*, the PFRA and the extensive network of irrigation infrastructure under government control speaks to state support of irrigation. The state supported irrigation, at the expense of allocating resources to other developments or users, because of its central importance to settlement. The rest of the chapter explores why the state continues to support irrigation despite settlement being achieved.

3.1. Interplay with Electoral System

Irrigation's importance to the GDP of Alberta has declined as other industries developed over the course of the 20th century, notably the oil and gas industry. Yet irrigation's primacy in southern Alberta as a water user remained constant. This section explores the relationship between economic and political policy in southern Alberta – namely the state's continual support for irrigation to secure electoral seats in southern Alberta. Since irrigation was regionally concentrated in southern Alberta, shoring up irrigator support was an important factor in winning elections in southern Alberta. Indeed, the Progressive Conservatives (PCs) were in power from 1975-2012 in Alberta. The extent of the PCs dominance in southern Alberta will be discussed.

The political influence of irrigators raises the costs of not supporting irrigation for an incumbent party. The federal government's withdrawal from Alberta's water policy subsystem in the 1970s favoured irrigators because they theoretically had even more electoral influence on the provincial government. The incumbents have two options on how to allocate their resources in the water policy subsystem. They can either support irrigation, or support alternative water uses. Initially, supporting irrigation was in the state's interest since irrigation was instrumental to the state's objective of settlement in southern Alberta. By the 1970s, southern Alberta was home to the most irrigated land in Canada (Heinmiller, 2016) and the issue of northern expansion into the prairies by the United States was a moot point. So why did the provincial government continue to support irrigation, to the point where the 1970s saw unprecedented growth in irrigated areas in southern Alberta? The incumbent's political party's need to secure southern voters to maintain electoral power in Alberta is one plausible answer to this question.

3.2. Political Incentives

Interest in the Oldman River Dam dated to 1912 and continually resurfaced during dry spells in the Oldman River sub-basin (Heinmiller, 2016). Irrigators and those in favour of supply-side water management argued that a dam on the Oldman River would provide greater storage and control of river flows (Sproule-Jones et al., 2008). Recurrent water scarcity was constraining irrigation development in the Oldman sub-basin (Schmidt, 2011). This sub-basin was an area in which the Alberta PC's were hoping to make inroads during the 1975 election (Heinmiller, 2016), their first as the political incumbents. Proponents of irrigation in southern Alberta successfully lobbied the province for a dam that invaded traditional indigenous lands, displaced

anglers, upset local landowners, and made the province the target of every legitimate environmental group in North America (Sproule-Jones et al., 2008).

In the model, the incentives remain the same for irrigators. Thus, irrigators continued to advocate for state support. For the state, the need to settle the prairies and foster agricultural development had been met. However, for the incumbent provincial government, the threat posed by the failure of settlement was replaced by the threat of not securing southern voters. For irrigation to persist as a sub-game perfect equilibrium, a credible threat or reward must be present. State support for irrigation cannot be taken for granted. The incumbent party supported irrigation because it had an incentive to do so. In the early 20th century the threat the state (federal government) faced was the possible failure of securing agricultural development and settlement. In the 1970s, the reward for the state (incumbent provincial government) was votes in the SSRB.

Support for irrigation was inexorably linked with supply-side water management because of the infrastructure required to divert, distribute and store water in the region. The Oldman River Dam was just a continuation of the relationship between the state and irrigators which began after the *Northwest Irrigation Act* was enacted in 1894. Indeed, since the 1920s, inter-basin water diversions were part of Alberta's water policy discussions (Heinmiller, 2016; Schmidt, 2011). In the 1970s, these large inter-basin projects were viewed as the logical next step in water management once water resources in the SSRB were exhausted.

However, by the 1990s these inter-basin projects had become politically untenable and were even banned by the *Water Act* (1999). Proponents of the advocacy coalition framework attribute

this change to changing policy core beliefs in the water policy subsystem (Heinmiller, 2013). These changes were precipitated by opposition to Oldman River Dam by environmental and conservation groups. By mobilizing public opposition, a coalition of environmentalists and conservationists was able to change the policy orientation – slightly – to a more demand-oriented governance structure according to this framework (Heinmiller, 2016). This framework extensively details how opponents to the Oldman River Dam were successfully able to mobilize and advocate for change (Heinmiller, 2013; Heinmiller, 2016). However, this framework does not provide a full picture as to how these advocacy efforts changed the incentives faced by the incumbents vis-à-vis irrigation. In the following section, a non-cooperative sequential game will illustrate the incentives faced by the incumbent provincial government, to continue its support for irrigation.

4. The Political Game

With the use of the analytical model, the incentives of the state to support irrigation as a means to electoral success are examined.

4.1. Game 1 – Electoral Success in the Absence of Advocacy

Understanding the game's implication for water policies requires calculation of the equilibrium outcomes. To begin this step, consider the sequence of choices made by the players. The game depicts uncertainty over the water availability in southern Alberta through a non-strategic player called the climate (W) who has the first move (Figure 6). Average precipitation occurs with probability π in southern Alberta. There is a probability $1-\pi$ of a drought. The nonstrategic player is a convenient way to express the uncertainty facing the second player, who must choose prior to knowing the availability of water.

Figure 6: Water Policy Choice under Uncertainty

After the nonstrategic player, the state or incumbent provincial party (S) moves and may decide to:

- 1) Support irrigation;
- 2) Support alternative water uses.

The dashed ellipse around the incumbent's two decision nodes in Figure 6 indicates that the incumbent does not know the availability of water at the time of its decision.

Irrigators (F) move after the incumbent and must decide whether to:

- 1) Support the incumbents by voting to elect the incumbents;
- 2) Vote for the opposition party (O).

To simplify the decision tree, it is assumed the winner of an election implements its policy platform. It is assumed the incumbent or opposition commit to their platforms well in advance of the election. Voters, therefore, have more information about the availability of water than do the parties when they make their decisions. The outcomes are summarized as follows:

- 1) if the incumbent wins the election on a platform of Irrigation, the outcome is A (continual state support);
- 2) if the incumbent wins on a platform of supporting Alternative Uses, the outcome is C (state still wins);
- 3) if the opposition wins the election the outcome is B.

The preferences of irrigators and non-irrigators (U) are given in Table 5. It is assumed the incumbents and opposition care only about winning the election and obtain 1 if they win and 0 if they lose. Thus, the election is a zero-sum game from the perspective of the political parties.

Irrigators are the pivot and their preferences depend on the availability of water. During average (normal) times, irrigators (F_N) prefer the incumbent's water policies favouring irrigation (A) to the opposition's water policies (B) to the incumbent's alternative uses policies (C) ($A > B > C$).

Irrigators preference for state-support of irrigation is obvious given the results of the earlier model. This model assumes irrigators prefer $B > C$ because voting for the opposition when irrigation policies are not on the agenda for both parties represents a credible threat from irrigators to the incumbents.

Table 5: Preferences of Irrigators (F) and Other Water Users (U)

F_N	F_D	U
A	A	B
B	C	C
C	B	0
0	0	A

For the incumbents, a decision to:

- 1) Construct the Oldman Dam for example, is analogous to an irrigation policy (A);
- 2) Foregoing the construction of a dam is (C);

Any policy proposed by an opposition party after winning an election is analogous to B. During a drought however, irrigators (Fd) prefer the incumbent's alternative policies to the opposition's policies, ranking the three outcomes as follows: $A > C > B$ (Table 5). Promoting irrigation centric water policies in droughts will benefit irrigators but may hurt junior license holders when the water supply is low and can impact communities and industries that are downstream from irrigation such as a processing plant (Rood, 2010). Irrigation districts have always been conscious of the appearance of having secure water while the rest of the SSRB is facing acute shortages and have shown a willingness to share water in such times (Bjornlund et al., 2014; Rood, 2010). Non-irrigators rank the outcomes as B, C, A regardless of the availability of water.

The subgame perfect equilibrium is identified through backward induction to determine the outcome of the game. The choice of irrigators at the four nodes near the end of the game are considered. If water availability is normal, irrigators prefer the incumbent's irrigation policies. Thus, if the incumbent offers irrigation policies, the outcome is A. If the incumbent decides to support alternative water uses instead of irrigation, irrigators prefer the opposition (B), which represents a credible threat to the incumbent government. During droughts irrigators prefer the incumbent over the opposition regardless of the incumbent's choice of water policies. This leads to the following behaviour by irrigators:

- 1) during average water availability, irrigators choose the incumbent if the incumbent supports irrigation policies;

2) irrigators always choose the incumbent during droughts.

Irrigators' behaviour conditions the incumbent's decisions. The incumbent government does not know whether there will be a drought. Because the incumbent government wins regardless of its decision during droughts, and because it wins during times of average water availability only if it proposes irrigation policies, they will propose irrigation policies all the time. This decision allows the incumbent party to win elections regardless of how much water is available.

The empirical evidence supports the model results. In the elections of 1971 and 1975, Alberta's legislature was comprised of 75 single member electoral divisions. 32 of those electoral divisions were located in the SSRB, approximately 43% (Elections Alberta, 2019). The PC's were elected in 15 of those 32 electoral divisions in 1971. By committing to construct the Oldman River Dam, the PCs were attempting to shore up irrigation votes (Heinmiller, 2016). In the 1975 provincial election, the PCs were elected in 28/32 electoral divisions within the SSRB (Elections Alberta, 2019). This region of Alberta accounted for 37% of the seats won by the PCs in 1975, a significant increase from the 20% in 1971 (Elections Alberta, 2019). The election of 1979 further cemented the relationship between the PC's and the irrigation voters in the SSRB. There were 79 seats in the provincial legislature in 1979 with 34 electoral divisions within the SSRB. The PC's were elected in 31 of those 34 divisions (Elections Alberta, 2019). The region accounted for 39% of their share of seats in the provincial legislature. Southern Alberta experienced droughts in 1977, 1984, 2001-2002 and 2015. In the elections following these droughts – 1979, 1986 and 2004 – the incumbent PCs won 91%, 86% and 87% of the available legislative seats in the SSRB (Elections Alberta, 2019). The results of the 2015 election will be discussed further below.

4.2.Game 2 – Impact of Advocacy

Considering the impact of advocacy by environmental and conservation groups, or junior license holders, adds a fourth move to the existing game. Non-irrigators (U) may apply political pressure (protests, advocacy, etc.) to the incumbent's set of water policies. Since environmental and conservation groups were a new coalition without support in the legislature (Heinmiller, 2013) their actions do not constitute a veto. Instead the payoff D represents an outcome where irrigation policies are enacted despite popular opposition and the incumbents (S) still win the election. As such, the actions of Non-Irrigators increase the political costs of implementing irrigation policies. Thus, Irrigators prefer D to B and C when water availability is normal (Table 6). However, during droughts Irrigator preferences are $A > C > B > D$. Non-irrigators prefer B and C to D, but prefer D to A. The preferences of the two players are otherwise unchanged from the three-move game.

Table 6: Preferences of Irrigators (F) and Non-Irrigators (U)

F_N	F_D	U
A	A	B
D	C	C
B	B	D
C	D	A

This game has sixteen end nodes (Figure 7). However, there are only four possible outcomes, making it easy to determine the subgame perfect equilibrium. In the game's last move, Non-irrigators must choose between the outcome arrived at by the previous moves or apply political pressure to arrive at D. Because Non-irrigators prefer D only to A, they will only apply political pressure when the previous move could trigger A. Thus, Non-irrigators apply political pressure only if Irrigators choose to support the incumbent party and when the incumbents decide to

implement irrigation policies. Thus, Non-irrigators apply political pressure only at their first and fifth decision nodes (nodes are numbered from top to bottom).

Figure 7: Water Policy Choice with Advocacy

Working backwards, the next set of decision nodes are for irrigators, who take Non-irrigators behaviour as a given. Irrigators assume that environmental groups and non-irrigators will oppose policies that favour irrigation. When water availability is normal, if the incumbent party promotes irrigation policies and if irrigators continue to support them:

- 1) The outcome is D for irrigators;
- 2) Outcome D is preferred to either outcome B or C.

Working further backwards, the incumbent's choice of whether to propose reform or irrigation policies is conditioned on the choices irrigators will make. If the incumbent party proposes alternative policies:

- 1) Irrigators will not support the incumbent's because irrigators prefer B to C;
- 2) Non-irrigators will not apply any political pressure since both B and C are preferred to A (status quo which maintains the primacy of irrigation)
- 3) To avoid losing an election, the incumbent party will always propose irrigation policies when there is average water availability to maintain irrigator support. Due to opposition from Non-irrigators, the outcome is D instead of A.

While Non-irrigators do not possess a veto, they do have the ability to make continual irrigation support politically unpalatable during drought years. During drought years, if irrigators support the incumbent's irrigation centric policies, the outcome is D. This outcome is the least preferred outcome for irrigators due to the protests of non-irrigators who have been left out of water policies during droughts. As a result, irrigators will not support the incumbent party if the party proposes irrigation policies in drought times (B). The incumbent party will not propose irrigation centric policies during drought years.

To summarize these outcomes, while taking the behaviour of Non-irrigators as a given:

- 1) The incumbent party always proposes irrigation policies to attract the pivot (irrigators) during average water availability;

- 2) During droughts, irrigators always support the incumbents (as shown in Figure 7) but the incumbents put alternative water policies on the agenda to placate non-irrigators.

In the equilibrium of this game, the incumbent party always dominates elections and will promote irrigation policies and promote alternate policies during drought years. The presence of environmentalists and conservationists actively advocating against existing water policies will temper the incumbent's support for irrigation during drought years.

The *Water Act* itself is a testament to the impact of the environmental coalition. The introduction of licensing moratoria to curtail the expansion of water use, the conservation holdbacks on license transfers and the presence of environmentalists on basin advisory committees illustrates the influence of this coalition (Heinmiller, 2016). After a drought in southern Alberta in 2001-2002, this coalition's influence led to the adoption of Alberta's *Water for Life* strategy which prioritized water conservation primarily in southern Alberta (Heinmiller, 2016). In addition, no new dams have been constructed in southern Alberta since 2004. The environmental coalition advocated for these changes continually since the provincial government's decision to construct the Oldman Dam in the midst of a drought in the late 1970s.

4.3. Implications

The two models in this section have significant implications for the persistence of irrigation in southern Alberta, despite the presence of other, potentially more valuable water users. The regional concentration of irrigation makes securing the votes of irrigation supporters crucial to electoral success in Alberta. This regional influence essentially makes irrigators the pivot which both the incumbents and opposition seek to attract. To maintain their electoral power, the incumbents would continue to support irrigators as long as water availability is 'normal' and

would always commit to support irrigators during a drought because they would not know when a drought would occur. This relationship models the narrative where irrigators and water policies favouring development were synonymous with the ruling PC party throughout the late 20th century.

Since environmental groups do not possess the same electoral influence as irrigators, they cannot prevent water policies that favour irrigation. One reason is the fragmentation of the various other interest groups within the water policy subsystem. A variety of interests compete for the attention of policy makers. The water policy community is diverse, with no coherent focus (Schmidt, 2011; Sproule-Jones et al., 2008). Facing no organized alternative, the traditional agricultural sector will continue to dominate the decision-making process in Alberta. There are over 400 environmental groups within the province with differing objectives (Heinmiller, 2013). Some groups have local objectives while the others advocate on a provincial or national level (Sproule-Jones et al., 2008). However, they can make these water projects unpalatable by raising the costs politically during droughts. This model implies that water reform policies make the political agenda only during times of water shortage. This model also implies that the change in water policy exhibited by the *Water Act*, was not just due to a change in policy core beliefs. This change was due to sustained pressure from advocacy groups which gained salience during opportune water shortages.

The models also imply that support for irrigation, both in the past and currently, is contingent on exogenous factors such as climate. While this conclusion is obvious, these models show that change is more likely when the frequency of droughts increase and when a credible opposition to

irrigation interests from environmentalists' forms. The model and empirical evidence show that irrigators support the incumbent's during droughts regardless of water policies. However, the addition of Non-irrigators, and coordinated advocacy can lead to a change in water policy proposals by the incumbent party. Some climate projections predict less streamflow and more frequent droughts in southern Alberta as the 21st century progresses. If these projections are accurate, the costs of maintaining the current equilibrium may be too high. Increased water shortages will lead to more advocacy and could lead to more reform.

The model identifies the political position of irrigators as crucial for maintaining the current equilibrium. It is important to note the water policy subsystem of southern Alberta exists within the larger policy system of Alberta. This subsystem has been dominated by irrigation and its proponents. However, with increasing urbanization and the salience of the oil and gas industry – both in southern Alberta and especially in northern Alberta – the political landscape of the province has changed since the *Northwest Irrigation Act* was signed in 1894 and continue to evolve. These changes have implications for irrigators and their ability to maintain “hard power resources” (Heinmiller, 2013) and remain the pivot in electoral politics.

Recent changes to the political landscape of Alberta have impacted the water policy subsystem of southern Alberta. Irrigator support for the PCs declined in 2012 and irrigators abandoned the PCs outright in 2015 in favour of the Wildrose party, allowing the NDP to win a majority government in the Alberta legislature. In the 2012 election 42 out of 87 legislative seats were located within the SSRB. The PCs won 24/42 of those seats (Elections Alberta, 2019). The proportion of seats won in this region in 2012 shows a significant decline in PC support. In the

2015 election, support for the PCs in the SSRB was virtually wiped out. The PCs won only 8 out of the available 42 seats (Elections Alberta, 2019). In 2015, the PCs were reduced to third party status when the Alberta NDP was elected.

Water policy was not a high priority for the NDP, which was preoccupied with the transporting of oil and climate change policies including carbon pricing. By 2015, the economic future of the province as a whole was tied to the oil sands and the energy sector instead of irrigation over 100 years ago. The election of 2015 can be characterized as an external shock (Heinmiller, 2016; Thelen, 1999) to the water policy subsystem of southern Alberta, a shock that shifted the balance of power electorally and altered a long-held coalition between the PCs and voters within the SSRB. A close examination of the platforms of the parties with respect to water infrastructure projects does not reveal any striking differences. Both the PCs and the Wildrose party emphasized the importance of infrastructure projects in their campaigns. The main cause of electoral disruption in Alberta was the state of the oil sector. By 2015, oil prices had fallen by half from the previous year and resource revenues had declined by 67% from \$2100/capita to \$680 per capita. Irrigators were still the pivot electorally but continuing to support the PCs in an environment with rapidly declining oil prices seemed unpalatable for most of the electorate. Even though the provincial NDP did win the 2015 election, they failed to attract the pivotal votes in SSRB which were split between the Wildrose party and PCs. The influence of this constituency was illustrated with their support of the United Conservative Party in 2019. Even though irrigation is no longer the major contributor to GDP, the influence of this particular group/industry in southern Alberta still remains.

5. Conclusion

The rules governing water allocation in southern Alberta were established in the political realm. Institutions that create credible commitments are central to the political foundations of an economy and the institutions governing water allocation in southern Alberta were no different. Irrigation was essential for the federal government's plans of westward expansion and it was a significant contributor to Alberta's GDP throughout the 20th century. Maintaining and developing the economy of southern Alberta required that the system of prior allocation be protected from political interference. With the growth and expansion of southern Alberta, demand for water from different industries and users increased. Other industries emerged as important to the GDP of the province and awareness of environmental water needs also increased over the course of the 20th century and continue presently. In the face of this political uncertainty and controversy over their rights, irrigators sought to maintain the water governance regime and their way of life.

The primacy of irrigation in the water policy subsystem of southern Alberta resembles an equilibrium. It is tempting to explain this persistence as a case of path dependence borne out of the irrigation's central role in the development of the province. However, a change in core beliefs in the province and a change in the economic conditions has not altered current distribution of water in the SSRB. The actions of irrigators and proponents of rural economic development and the actions of the incumbent government pursuing electoral victories reinforces this current allocation. Persistent drought coupled with consistent advocacy for water policy reform may change water allocation moving forward.

Southern Alberta's water policy subsystem is inexorably linked to the political and economic foundations of the region and the province at large. These political and economic conditions were essential in creating the prior allocation regime and maintaining the primacy of irrigation in southern Alberta to date. While irrigation's importance to the economy of southern Alberta has declined, its primacy with respect to total water allocations has not. The changes introduced by the *Water Act* have changed water policy to a degree, yet the supply driven management paradigm and infrastructure remain, in part due to the political importance of the irrigation belt in electoral politics of Alberta. A fundamental alteration of the water policy orientation will require a change in both the political and economic foundations of the region, as well as a consideration of the vast water conveyance infrastructure.

Advocacy groups have raised the costs of maintaining irrigation's primacy, but as long as this constituency can remain the pivot in electoral politics, irrigation's primacy is likely to remain. Cities are a far more likely constituency to challenge the influence of irrigation groups electorally in southern Alberta. Cities and suburban areas within Alberta can have a large electoral influence because they have a concentration of legislative seats and, especially in southern Alberta, water issues are salient. Even if cities play a bigger role in the water policy subsystem, the coalition dynamics are unpredictable. Cities could form a coalition with environmental groups and advocate for more environmental flows for example. Cities could also form a coalition with agricultural interests and advocate for more dams which would increase water storage and reduce flooding in southern Alberta. If cities emerge as a viable interest group with a single policy issue animating them, the party that proposes a platform that can attract more than one interest group may have a sustained period of electoral dominance. The wildcard

is climate change. Any long-term change to the supply of water will strengthen the calls for change in the water policy subsystem and may change the incentives of actors with respect to water policy.

Going forward, more institutional layers which prioritize environmental conservation may be proposed and implemented in southern Alberta. The layers may be consistent with the principles espoused by the *Water Act* and may incorporate the concerns of environmentalists, agricultural groups and many other stakeholders in the basin. To date, the environmental coalition has limited irrigation's expansion and the construction of dams and given the potential impacts of climate and the need to accommodate other water users, this trend will likely continue. However, irrigators are still the pivot electorally due to their regional concentration. If droughts occur more frequently, environmentalists will have more political influence to propose more changes to the water allocation regime. However, unless this or another coalition can coalesce into a regionally concentrated voting bloc, existing water rights will remain secure as will the FITFIR principle.

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Chapter 5: Conclusion

1. Introduction

This dissertation has examined issues of water allocation, governance and institutional change. More specifically, these chapters examine how southern Alberta's water allocation regime is layered, the potential welfare gains from water reallocation and the political and economic barriers to changing the current equilibrium with respect to water allocation. The main lessons from this dissertation are:

- 1) A misalignment between entrenched institutional arrangements and new institutional instruments can limit the effectiveness and scope of new instruments;
- 2) Southern Alberta's water allocation regime is not fungible across multiple dimensions;
- 3) Enhancing the fungibility of the water rights regime should be prioritized;
- 4) Reallocation of water resources can increase the economic benefits to water use;
- 5) Prior allocation leads to sub-optimal allocations of water and ensures water is not reallocated to higher marginal users of water;
- 6) Irrigation's primacy within southern Alberta was initially tied to Canada's desire to settle and develop the prairies;
- 7) The regional concentration of irrigation magnifies the electoral influence of its proponents in Alberta.

As a whole, the transition of water governance in southern Alberta is explored. The difficulties in transitioning from one governance model to another is encapsulated by the misalignment between the water market and the legal framework it operates under – the prior allocation regime. This misalignment and the non-fungibility of water rights is the focus of chapter two. The prospective gains of a transition are explored in chapter three. The constrained optimization

shows how water reallocation in the SSRB could lead to an increase in economic benefits throughout the basin. The chapter also shows the potential pitfalls of widescale water reallocation. The entire enterprise is dependent on the reuse of return flows and the potential impact of climate change on water supply should be a concern – both for consumptive water users and instream protection areas. Chapter four explores how the current equilibrium continues to persist. This concluding chapter does not repeat the conclusions of earlier chapters, but instead highlights the implications of this transition and assesses its limitations in supporting the broader argument of this dissertation: that southern Alberta’s water allocation regime is stable due to how it coevolved alongside the economic and political institutions of the region.

2. Dissertation Review

The water policy orientation in southern Alberta has undergone a transition, albeit a limited one, from supply side management to something more demand-oriented (Heinmiller, 2016), and a water allocation regime where environmental concerns are more salient. This transition will become increasingly more salient if reduced streamflow projections come to pass over the 21st century. This transition is already in progress and water policy in southern Alberta has changed to a degree since the *Water Act* came into force (Heinmiller, 2016). It may be more apt to conceptualize the water allocation regime as in transition rather than transitioned (Meadowcroft, 2009). Transitioned implies not just a process of change, but an arrival (Pahl-Wostl, 2007). As the current water allocation – i.e. the dominant water user in southern Alberta – has not changed and the ‘transition’ is one of degree rather than a change in kind (Heinmiller, 2016), it is more accurate to describe the southern Alberta’s water policy subsystem as one undergoing a gradual transition.

The question is, what is the water policy subsystem transitioning into? The optimistic answer, especially with the anticipated changes in climate is an allocation regime where there is more flexibility with respect to water supply, an allocation regime that includes the interests and concerns of First Nations and a regime where risk is shared in a more equitable manner among water users. A more equitable risk profile is counter to the prevailing priority system and may require a shift to where water allocations are not dominated by one sector. The fact that senior license holders have ceded stored water resources and have not always applied their seniority (Rood, 2010) is a sign of flexibility within the regime but also a tacit admission that the priority system is inadequate to deal with some of the water supply issues of the 21st century.

A transition in water policy in southern Alberta is becoming increasingly important. Transitions are understood as processes of structural change in policy subsystems (Meadowcroft, 2009). They involve a shift in the dominant rules of the game. These transitions can often transform established governance practices and result in a change of the prevailing equilibrium within a policy subsystem (Meadowcroft, 2009). It is now widely recognized that transforming institutional arrangements which underpin production and consumption patterns in core sectors is essential if human activities are to continue with impending climate change (Meadowcroft et al., 2009). Water allocation must transition to avoid serious supply shortages if some of the climate change projections do indeed come to pass.

A transition in the water policy subsystem of southern Alberta could be appealing to those who question the current governance model and current equilibrium of water allocation. Transforming

the water allocation regime is far from trivial, as shown by the resistance by irrigators and senior license holders who have historically benefited from more secure water licenses. In addition, southern Alberta's water policy subsystem overlaps with other subsystems including the economy and political environment. This work focuses on the specific boundaries of the water policy subsystem, but it is apparent that water policy evolved in conjunction with the economic and political institutions of the province and its transition will inevitably be linked with transitions in these other subsystems. Actors within the water policy subsystem are bound to be concerned with their place in future institutional arrangements. In this context, senior license holders prefer the status quo and their determination to maintain this status quo explains the layering of the water allocation regime. The political struggles between the irrigation and environmental coalitions, which emerged after the decision to construct the Oldman River Dam, might become more acute if streamflows in southern Alberta decline due to climate change.

The overarching concern with water allocation in southern Alberta is the perceived inflexibility of the prior allocation system. Allocating water based on historical practices results in lock-in. Allocating water based on what was needed in the late 19th and early 20th centuries may not be adequate for the challenges and economic needs of the current era and for the needs of the future. There are two ways of addressing issues of lock-in. One is to incrementally adjust existing practices to address any perceived problems (Pierson, 2004; Thelen, 1999). Layering the *Water Act* on top of existing institutional structures is an example to this approach. New instruments such as the water license transfer system, conservation objectives and the environmental holdback were added to address specific supply and environmental challenges associated with prior allocation. The second approach is to fundamentally alter the design of institutions (van der

Heijden, 2011; Meadowcroft, 2009). The rationale underpinning this approach is that it may turn out that incremental changes are not enough to address the problems with existing institutions, either because the problem is more acute or the resistance to change is greater than anticipated (Meadowcroft, 2009). Changing the existing distribution of water allocations in southern Alberta's water policy regime requires either time or much more than the layering of new policy instruments. A change in the economic and political conditions may be required.

Chapter two discusses Australia and Colorado's water allocation regimes and compares them to the SSRB with respect to the fungibility of water rights. Australia's approach involved a complete overhaul of their water entitlements and an implementation of a system based on proportional shares. Neighbouring Saskatchewan may also provide insights on how to fundamentally alter a water allocation regime. Saskatchewan established a centralized water regulator with almost total authority over water allocation and use in the province that uses its authority to allocate and reallocate water based on pressing needs, thereby allowing for adaptation to periodic water shortages (Heinmiller, 2018). Saskatchewan has pursued this strategy since 1984, eschewing the prior allocation system it had inherited from the federal government and also avoiding the water license transfer strategy adopted in Alberta (Heinmiller, 2018).

The case of Saskatchewan is interesting as it represents a different policy innovation to Alberta (Heinmiller, 2018), in an area with similar institutional origins with respect to water allocation. Alberta undertook an incrementalist approach to water policy reform as exhibited by the layering of new policy instruments, while neighbouring Saskatchewan attempted to fundamentally alter

their water policy subsystem. As it stands, misalignment of southern Alberta's water allocation regime reflects acute social struggle regarding the character of transition in southern Alberta's water policy subsystem (Heinmiller, 2013). The experience with water markets shows that incremental changes may not be enough. At the very least the water market needs to be supplemented with new instruments such as defining consumptive water use or the non-fungibility of water rights must be addressed. The links between the political system and the water policy subsystem, especially the pivot position electorally held by irrigators points to the need for system innovation. The changing dynamics of the province as a whole may lead to a declining influence of irrigators politically and might allow for a more fundamental alteration of water policy.

Southern Alberta's water policy subsystem is not immune from shocks, both internal and external. For example, cities may agitate for a greater role with respect to water allocation, considering the increasingly urban population of the region. While Chapter four explored how irrigators have been an important pivot in electoral politics, the most salient issue currently in Albertan politics appears to be oil and gas.

3. Chapter Summary

This dissertation began by situating southern Alberta's water allocation regime within the state's policy to settle and develop the prairies in the late 19th century. The dissertation then reviewed the literature on water markets and the underlying logic of the prior allocation regime. To understand why water markets have not been fully embraced in southern Alberta, the institutional origins of prior allocation and how the water market was layered on top of the

existing water institutions were examined. Water license transfers are limited because their emphasis on individual transactions is different from the logic of public development espoused by the water allocation regime and because of the non-fungibility of water rights in the SSRB. Between 2003-2017, only 203 water licenses were transferred (Alberta Environment, 2017). Chapter two also adopted a fungibility framework designed to analyse energy systems (Bradford, 2018) and identified seven different characteristics in which the fungibility of water rights could be analysed in southern Alberta. Using this framework, the lack of fungibility based on the type of water rights that exist in southern Alberta, the way these water rights are defined, the degree to which they are transferable and the degree to which they are certain were identified.

The potential welfare gains from water reallocation were also examined. Using AQUARIUS, the water allocation regime of the SSRB was abstracted and water use was optimized to maximize total economic benefits in the basin. Using hydro-economic modelling, the impacts of return flows, increased water demand, reduced streamflow and pricing for environmental water use were explored. These modeling simulations were done while maintaining the institutional constraints present in the SSRB. As such, the results indicate what is possible given the existing institutional arrangements. The results indicate that water reallocation, including return flows, can increase welfare in the SSRB. However, any prolonged decline in water supply could present significant challenges for water allocation to both consumptive water users and the environment in the SSRB. These scenarios were simulated in an environment devoid of transaction costs.

Despite the potential welfare gains from water reallocation the current equilibrium – where irrigation is the dominant water user – persists and has persisted for over a century in southern

Alberta. The underlying incentives of irrigators and the state were examined to understand why this current allocation resembles an equilibrium and what factors have led to its continual stability. The importance of irrigation to settlement initially and the importance of the irrigation belt electorally in the late 20th century is a possible explanation of how the current allocation has persisted over time. Environmental advocacy groups have been able to steer water policy in a more demand-oriented direction, especially during periods of drought. This trend is likely to continue; however, the seniority and water use patterns of irrigators is unlikely to be threatened.

4. Implications

The results of Chapter two imply that if the non-fungibility of water rights is not addressed in the SSRB, water license transfers will be limited to a niche role in southern Alberta. Proponents of water markets, who continually highlight the potential economic gains and redistributive properties must first ensure water rights are defined consistently, are transferable with each other and have similar levels of certainty. Activation of sleeper licenses is another factor to consider with the water transfer system. Sleepers are water licenses that existed prior to the introduction of the water market but were not actually used by licenses or were only partially used (Young, 2014). Only about 68% of licensed allocations in southern Alberta are fully used (Bennett et al., 2017). The introduction of the market has potentially activated the unused portion of these licenses which can be sold or traded rather than be used for environmental purposes. If this occurs there is potential that the water transfer system will result in an increase of water withdrawals within the SSRB at the expense of the environment (Young, 2014).

One lesson to take away from the introduction of water markets in Australia is the importance of addressing sleeper rights before the introduction of water license transfers (Young, 2014).

Australia's initial experience with the introduction of water markets led to an increase in withdrawals and widespread environmental degradation before the water transfer system was overhauled to account for sleeper rights (Wheeler et al., 2014; Young, 2014). If the water market is to become a more prominent water sharing instrument the consequences of activating sleeper rights must be examined. One solution, as mentioned in chapter two, is to define water licenses based on historical consumption levels and ensure only amounts that have been consumed can be traded.

Defining water licenses in terms of the water consumed will help make licenses more fungible along the definition and transferability dimensions of the fungibility framework. Defining consumptive water use amounts will also help address third party impacts. Explicitly defining the consumptive amounts users are entitled to, provides certainty to both upstream and downstream water users. License holders could transfer the consumptive portion of their licenses without fear of third-party impacts or a long review process.

Better instrument design can certainly align the principles of the water transfer system with the historical water governance practices in southern Alberta. But viewing the lack of water market activity as a problem of instrument design assumes that license holders, especially senior license holders, want to use the transfer system. A well-functioning water market requires both willing buyers and sellers. Previous research in southern Alberta indicates that irrigation districts are reluctant to part with their licenses (Rahimova et al., 2016). The water allocation regime was not

overhauled to accommodate the introduction of water license transfers. Indeed, this dissertation has described in detail how the license transfer system was just layered on top of an existing allocation regime. Maintaining the traditional institutional arrangements was of paramount importance to senior license holders. Their preference for maintaining the status quo, which was established in the 20th century implies that a water market, which requires a reallocation of water from senior license holders, cannot be the only mechanism for water sharing in southern Alberta.

Better instrument design includes integrating groundwater analysis and modelling into water management. Alberta's groundwater resources must be effectively mapped out and the amount of withdrawals by different users must be recorded. This data will help policy makers and users understand the interaction between groundwater and surface water on a basin-wide level. To what extent is groundwater a substitute for surface water and how sustainable is the use of groundwater in certain sectors such as municipal or agricultural use? These are questions that can only be answered after accurate monitoring of groundwater is completed. Indeed, regional water allocation models should include groundwater analysis to determine how increased water demand projections or reduced streamflows will impact water in southern Alberta, as opposed to just surface water.

Other mechanisms of water sharing, such as assignments or amendments of irrigation district licenses have been explored and have the potential to reallocate water from senior to junior license holders in southern Alberta (Bennett et al., 2017). These mechanisms do not rely on senior license holders to relinquish their entitlements and are more aligned with the community driven water management practices in southern Alberta as opposed to the individual transactions

espoused by a water market. Pursuing temporary water assignments and water sharing through leases may be more feasible mechanisms of acquiring water from irrigation districts concerned with relinquishing long-term control of their entitlements. The use of storage reservoirs also provides an opportunity to address fungibility concerns and facilitate water sharing across different years. If stored water can be carried over to the following year it may provide water users with more flexibility and provide more certainty to prospective buyers and sellers. Finally, conceptualizing stored water as unnatural flow provides flexibility in how to manage this resource during times of shortage (Rood, 2010). This flexibility will allow decision makers to allocate the stored water to address pressing needs such as ensuring environmental flows and riverine habitats receive sufficient flows during shortages and allocating water to consumptive users in need.

Conducting a constrained optimization of water allocation in Chapter three reveals that reallocating water to higher valued users can increase economic welfare in the SSRB. This analysis reveals that any welfare improvements are dependent on the continual reallocation of return flows. Return flows play an important role in water allocation, as they support instream flow needs and are available for reallocation to different users downstream. These return flows are also important to fulfill instream objectives within the SSRB. Continually reallocating return flows may help address water quantity issues within the SSRB but may pose questions regarding the timing and quality of these flows.

The potential welfare gains from water reallocation have been used by proponents of water trading to advocate for facilitating water markets in the SSRB (Cutlac & Horbulyk, 2010; Weber

& Cutlac, 2014). While the model does show welfare gains, it must be noted that these gains occurred in a transaction costless environment. With actual water trading in the SSRB, transaction costs abound. The model reallocated water wherever it was feasible. This assumes that water users are able to compensate for third-party effects, which can arise due to binding flow constraints on third parties or water conservation objectives for example. In reality, some trades may be blocked because of the potential impacts on third parties. In the case of the water market, transaction costs arising from the 10% conservation holdback and the review process may deter water trades. Therefore, the actual reallocation of water, be it through a transfer system or other mechanism, will lie between the current allocation and the optimized base case scenario.

Finally, the reallocation of water may not adequately protect environmental flows in the SSRB. In the event of increased scarcity, water resources may not adequately support licensed water users and instream protection areas. Since the environment is not a licensed user of water, reallocating flows may not address the environmental flow needs in the event of continued long-term scarcity in the basin. The key challenge the environment faces is the number of senior license holders ahead in the queue. The analysis implies there are at least two mechanisms for addressing these environmental concerns. One is a direct mechanism of allocating water to the environment. The model simulated this scenario as a rigid constraint. While this mechanism ensures the environment receives water, it may result in inadequate water for other users in the basin. The second mechanism is to buy back water for environmental purposes. This approach was simulated by recognizing the environment as a user of water with a willingness to pay. Under an environmental pricing scenario environmental water use will be dependent on how

much citizens, or the provincial government is willing to pay to reallocate water from irrigation or other senior users to the environment.

The models used in chapter four possess a single equilibrium. This allows for the change of a particular exogenous variable and form propositions about how the endogenous variables may change. This dissertation explored the conditions which define the current allocation of water in southern Alberta and tested relationships among strategically linked actors. The approach relies heavily on the theory of games. This approach offers a theory of structure. It provides insight into how structures create incentives that shape choices and shape collective outcomes (Bates et al., 2019). Even if the game's explanatory power, in terms of generalizability, is limited, the game reveals strategic problems and incentives actors face within southern Alberta's water policy subsystem. The propositions of the game on southern Alberta's water subsystem may not be generalizable but the analysis of strategic interactions between irrigators, the state and an opposing coalition provides opportunities for comparative analysis with other jurisdictions.

5. Recommendations

No single policy will address southern Alberta's water policy concerns. There is no panacea. What is important is to address contemporary issues of water allocation in a manner that provides flexible governance options. With this consideration in mind, the following recommendations are made:

1. Value non-consumptive water use. The valuation system may be up for debate but the fact that there is a value to non-consumptive water use is not. Non-consumptive water use, water conservation and instream protection are important components of social and

environmental systems and a criterion should be established to assess all existing and future water licenses for the benefit of these system in southern Alberta, and Alberta as a whole.

2. Supporting and recognizing a First Nations water governance mechanism in Alberta that is granted authority for water allocating and governing water use in First Nations' territory and which coordinates with other governing bodies as appropriate. This dissertation did not cover water allocation and water rights from the perspective of First Nations within southern Alberta. However, due to their historical claims on water resources, calls for reconciliation and justice and self-governance, First Nations within southern Alberta have a big part to play on how water is allocated going forward.
3. Enforcing minimum flows for the protection of instream areas and require the continuation of moratoria on the issuance of new water licenses.
4. Create a standard to assess potential impacts of water license transfers. Once the standard is met, transfers should go through.
5. Proposing measures to address the lack of fungibility of water rights within the SSRB. The proposed fungibility framework outlines which dimensions should be considered in addressing non-fungibility.
6. Consider redefining water rights in terms of consumption as well as diversion amounts. While this undertaking may be burdensome, it will provide Alberta with accurate assessment of consumptive water use within the province.
7. Unbundling water access rights from water use rights (i.e. agriculture, energy).
8. The fragmentation of surface and groundwater must be addressed. An allocation mechanism for groundwater that is harmonized with surface water must be implemented

so that existing water licenses are aligned with effective groundwater regulation and governance. Monitoring and a comprehensive assessment of groundwater resources is a necessary step.

6. Final Remarks

Water allocation problems in southern Alberta are not easily solvable. Water allocation involves a complex web of interdependent social and environmental factors that are not easily reducible and are subject to constant change (Heinmiller, 2016). Climate change and the lack of stationarity adds an additional layer of uncertainty. In their attempts to manage water resources, actors approach the problems of water allocation and governance based on their policy core beliefs and values and to strategically maximize their own preferences.

Water governance, particularly at large scales, is complex because it involves a large variety of actors who try to make sense of it based on their own strategic interests. The proponents of irrigation and environmentalists, for instance, approached water governance in southern Alberta with starkly different values and objectives, and advocated for conflicting policy programs based on these interests. The objective of irrigators was to continue along the developmentalist path, while environmentalists advocated for conservation. Both these objectives are normative implying that the conflict between these two groups is a political one (Heinmiller, 2016). In reality there are several more groups and interest groups with a normative stance on how water should be allocated, Alberta's First Nations being one group with several sub-groups within them. To exercise political power in the water policy subsystem, actors with similar interests tend to coalesce into advocacy coalitions, as shown through Heinmiller's use of the ACF. This

seems like an obvious observation. The number and types of advocacy coalitions vary in different contexts, but the tendency towards advocacy coalitions is quite clear. Another obvious observation is the importance of political power in the water policy subsystem. The importance of political power in water governance is often overlooked (Heinmiller, 2016). The development of southern Alberta's water allocation regime is tied to the political and economic influence of actors within the subsystem. Irrigation's dominance was due to its economic importance and the political influence of its proponents. The emergence of an environmental coalition has at the very least altered the policy options on the agenda with respect to water governance.

Political power is important, but water governance also involves actors collectively trying to design acceptable policy solutions and regimes. There are no optimal policy solutions to water allocation problems. The findings here shed some light on how policies are adopted in such situations, findings that can be built on by others to help policy makers and actors design policies that try and address the interests of multiple stakeholders and avoid policies that promote the primacy of a certain group over other stakeholders.

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Appendix 1

Object-Oriented Programming Framework

This appendix documents the basic architecture of the AQUARIUS software and discusses the advantages of using an object-oriented programming (OOP) framework, for modeling the hydraulic and mathematical connectivity of the South Saskatchewan River Basin (SSRB).

Objects contain properties that communicate with other objects and are controlled by rules determining how they act based on input data specified by the user (Diaz et al., 2000). The SSRB was modeled through OOP in Chapter three which included different components such as irrigation areas, municipalities, instream protection areas and various diversions etc. The water users in the SSRB were modeled as a node or object in the programming environment. A link between two nodes – such as a canal – is an outflow slot of an upstream component connected to an inflow slot of a downstream component (Diaz et al., 2005). AQUARIUS is depicted by the top-level diagram below (Figure 8).

Figure 8: AQUARIUS Structure (Diaz et al., 2000)

The Network Worksheet stores the other two basic class categories of AQUARIUS, the Water System Components and the Water System Links (Diaz et al., 2000). The Water System Components that make up a flow network are a series of nodes and links and are automatically displayed on the upper side of the screen. The user can move the components to any place on the screen. The Water System Components are displayed in the following diagram (Figure 9):

Figure 9: AQUARIUS Water System components (Diaz et al. 2005)

The user creates a flow network, or watershed, through a graphical user interface (Diaz et al., 2005). Each system component in AQUARIUS corresponds to a graphical node or link for the flow network created by the user (Diaz et al., 2005). The components are represented pictorially through the graphical interface (Diaz et al., 2005). To assemble a flow network, two or more nodes (water sources, reservoirs, powerplants, demand areas, diversions, or junctions) are placed in the Network Worksheet. These nodes are linked using canal/pipelines, from the Water System Components.

AQUARIUS model architecture

AQUARIUS uses an object-oriented programming language, specifically C++. The SSRB includes different types of water components (Diaz et al., 2005), including reservoirs, four cities, multiple diversions, seven irrigation areas, six instream protection zones which were represented

in AQUARIUS. Each of the aforementioned components are represented by a node in the programming environment, as shown in the figure below.

Figure 10:SSRB Representation in AQUARIUS

A portion of this network is depicted in Chapter three. Figure 10 depicts the entire SSRB that is abstracted for the optimization exercises.

Specifying Water Demand

Figure 11 and 12 show how the user interacts with AQUARIUS through its interface. For each node within the abstracted water basin, the user specifies economic or physical characteristics. These figures show the inverse exponential demand curves for the Red Deer node for different scenarios. To enter this data within AQUARIUS, the user must first choose the type of demand curve. For municipal and agricultural water users, AQUARIUS allows for the specification of constant and exponential inverse demand curves.

Figure 11: Inverse demand function produced by AQUARIUS for Red Deer (Diaz et al., 2005).

Figure 12: Inverse demand function for increased water demand scenario produced by AQUARIUS for Red Deer (Diaz et al., 2005).

As covered in Chapter three, AQUARIUS estimates parameter a and b as long as certain variables are known. The interface showing how this exponential fitting takes place is depicted

in Figure 13. Since estimates of choke prices for agricultural and municipal water users can be inferred and monthly water charges in the cities and irrigation districts are known, the user can use one of the three methods of fitting exponential functions in AQUARIUS. This exponential fitting provides the user with parameters a and b which are then specified for each node with an exponential inverse demand curve (Figure 11 and 12).

Figure 13: Exponential fitting in AQUARIUS (Diaz et al., 2005).

Mathematical Connectivity

AQUARIUS automatically derives the mathematical connectivity of the water basin's components from the linkages of the nodes within the network (Diaz et al., 2000). These linkages reflect the hydraulic connectivity – the direction of flow from one node to another (Diaz et al., 2000). The spatial arrangement of the network determines the hydraulic connectivity between different nodes. Where certain nodes (city or instream protection zone) are arranged within the network influences the decisions at the nodes further downstream. A series of links connecting

surface water sources, storage reservoirs and water users are used by AQUARIUS to automatically formulate the mathematical structure of the water allocation problem (Diaz et al., 2000).

AQUARIUS allows the user to access the mathematical connectivity of the network in the form of a table. Table 7 presents the mathematical connectivity of the aforementioned SSRB network and Table 8 presents the connectivity between nodes.

Table 7: Table of Mathematical Connectivity in Model Architecture

Table of Mathematical Connectivity for: Network2																	
D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	Decision Set
L1	L3	L10	L14	L16	L18	L21	L31	L43	L48	L57	L59	L62	L63	L73	L78	L87	Link Number
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 City_Medicine_H
0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-0.7 Div_3
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0 Bow_ID
0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0 Waterton_res
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0 Div_7
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0 City_RedDeer
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 Bow1
0	1	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	-0.3	0 Div_8
0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	-0.7 oldman1
0	0	-0.85	-1	0	0	-0.3	1	0	0	1	0	-1	0	0	0	0	-0.7 Oldman2
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0 City_Lethbridge
-0.3	1	-0.85	0	-0.85	-0.79	-0.3	1	-0.8	-0.65	1	-0.77	-1	1	-0.3	-0.3	0	-0.7 Apportionment
0	1	0	0	0	-0.79	0	0	0	-0.65	0	0	0	0	0	0	-0.3	0 Bow2
0	0	0	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0 Div_11
0	0	0	-1	0	0	-1	1	0	0	1	0	-1	0	0	0	0	-0.7 Div_14
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0 Div_15
0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0 Gleniffer
0	0	0	1	-1	0	0	0	-0.8	0	0	-0.77	0	0	0	0	0	0 Div_17
0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 UpgBow_slot
-1	1	-0.85	-1	0	-0.79	-0.3	1	0	-0.65	1	0	-1	0	0	0	-0.3	-0.7 Div_20
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0 EW_ID
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1 Div_25
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0 StM_T_ID
0	1	0	0	0	-1	0	0	0	-0.65	0	0	0	0	0	0	-0.3	0 Div_28
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1 UALMV_ID
0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0 StM&R
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 LethbridgeN_ID
0	0	0	0	0	0	0	0	0	0	0	0	0	1	-0.3	0	0	0 RD2
0	0	-1	-1	0	0	-0.3	1	0	0	1	0	-1	0	0	0	0	-0.7 Div_35
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 Bow
0	0	0	1	0	0	0	0	-1	0	0	-0.77	0	0	0	0	0	0 Div_37
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0 Mag_Ray_ID
0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0 Oldam_Lake
0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	0	0	0 Div_39
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0 Calgary
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0 IP

Table 8: Connectivity Between Nodes in Model Architecture

Table of Nodes: SSRB Network base case scenario					
No.	Name	Type	Price function	Upstream	Downstream
1	City_Medicine_H	MUNICIPAL	Yes	Div_26	Jct_34
2	Waterton_res	RESERVOIR	No	Jct_8	Div_38
3	Bow_ID	IRRIGATION	Yes	Div_29	Jct_39
4	Elkwater_Inflow	NATURALFLOW	No	–	Jct_30
5	Bow1	RECREATION	Yes	Jct_27	Jct_6
6	City_RedDeer	MUNICIPAL	Yes	Div_5	Jct_31
7	oldman1	RECREATION	Yes	Jct_16	Jct_3
8	Blood_Ind_catch	NATURALFLOW	No	–	Jct_32
9	Oldman2	RECREATION	Yes	Jct_24	Jct_25
10	Waterton_river	NATURALFLOW	No	–	Jct_33
11	Belly_river	NATURALFLOW	No	–	Jct_33
12	Bow2	RECREATION	Yes	Jct_39	Jct_25
13	Apportionment	CONSERVATION	No	Jct_17	–
14	City_Lethbridge	MUNICIPAL	Yes	Div_12	Jct_23
15	Glenifer	RESERVOIR & REC	No	Red_Deer_river	IP
16	Sylvan_catch	NATURALFLOW	No	–	Jct_28
17	Willow_creek	NATURALFLOW	No	–	Jct_7
18	UppBow_slot	RESERVOIR & REC	No	Bow_river	Bow
19	EW_ID	IRRIGATION	Yes	Div_9	Jct_35
20	StMary_river	NATURALFLOW	No	–	Jct_8
21	Bow_river	NATURALFLOW	No	–	UppBow_slot
22	LittleBow_river	NATURALFLOW	No	–	Jct_10
23	StM_T_ID	IRRIGATION	Yes	Div_37	Jct_4
24	UALMV_ID	IRRIGATION	Yes	Div_21	Jct_20
25	Red_Deer_river	NATURALFLOW	No	–	Glenifer
26	Oldam_river	NATURALFLOW	No	–	Oldam_Lake

27	LethbridgeN_ID	IRRIGATION	Yes	Div_36	Jct_24
28	StM&R	IRRIGATION	Yes	Div_18	Jct_14
29	Bow	POWERPLANT_VH	Yes	UppBow_slot	Jct_27
30	Gull_catch	NATURALFLOW	No	–	Jct_1
31	RD2	RECREATION	Yes	Jct_32	Jct_17
32	Elbow_river	NATURALFLOW	No	–	Jct_6
33	Oldam_Lake	RESERVOIR & REC	No	Oldam_river	Jct_7
34	Highwood_river	NATURALFLOW	No	–	Jct_40
35	Mag_Ray_ID	IRRIGATION	Yes	Div_15	Jct_19
36	IP	RECREATION	Yes	Glenifer	Jct_28
37	Calgary	MUNICIPAL	Yes	Div_11	Jct_22

AQUARIUS Source Code

The source code to the AQUARIUS modeling program is provided as a separate file with this dissertation (Diaz et al., 2005).

References:

- Diaz, G., Brown, T., & Sveinsson, O. (2000). Aquarius: A modeling system for river basin water allocation. *General Technical Report, USDA*.
- Diaz, G., Brown, T., & Sveinsson, O. (2005). *Aquarius* (Version V05) [Computer software]. USDA.