ASSESSING THE SUITABILITY OF THE MULTILEVEL GOVERNANCE FRAMEWORK OF THE LAURENTIAN GREAT LAKES BASIN TO SUSTAIN THE QUANTITY OF ITS STORED GROUNDWATER RESOURCES

ASSESSING THE SUITABILITY OF THE MULTILEVEL GOVERNANCE FRAMEWORK OF THE LAURENTIAN GREAT LAKES BASIN TO SUSTAIN THE QUANTITY OF ITS STORED GROUNDWATER RESOURCES

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LAY ABSTRACT

Water use in the Laurentian Great Lakes Basin (GLB), the world's largest freshwater store, has historically been subject to binational agreements between the United States and Canada, multilevel government statutes in both nations and court rulings. While persistent, sub-watershed scale groundwater storage (GWS) decline is not a widely reported issue in the GLB, places where they are observed are commonly in drought-prone and/or groundwater-dependent GLB communities. With growing human demand and climate stressors, this thesis adopts a proactive stance on addressing this emerging issue. As governance lies at the heart of maintaining GWS in social-ecological systems such as the GLB, this dissertation applies multidisciplinary methods to assess governance characteristics underlying growing groundwater insecurity in high-groundwater-stress situational contexts of the Basin. Findings highlight that the top-down GWS governance approach insufficiently leverages the strengths of local institutions to prevent groundwater insecurity. Findings also show that groundwater use and conservation standards have not been sufficiently based on the unique physical-environmental sustainability requirements of aquifers to maintain GWS, as they continue to be based on relatively limited 19th-century scientific understanding of groundwater flow systems. Largely unchanged over time, contemporary governance instead generally applies the same water use and conservation standards, originally developed to sustain surface water, to govern surface water and groundwater use. These conclusions inform recommendations for sustaining GWS in vulnerable locations, considering growing populations and climate uncertainties.

ABSTRACT

Water use in the Laurentian Great Lakes Basin (GLB) has long been governed by a framework of binational agreements between the United States and Canada, policies and decision-making standards of multilevel governments, and court rulings. Though groundwater quantity is not comprehensively monitored and groundwater insecurity is not widely reported throughout the Basin, in the context of rising regional populations increasing groundwater demand in high-use hotspots and climate change impacts simultaneously reducing aquifer recharge, this dissertation proactively examines the multi-scale interactions between multilevel governance and groundwater resources that can reduce sub-watershed scale groundwater storage (GWS) in high use and/or drought prone locales. Grounded on sustainable aquifer yield, adaptive governance and subsidiarity theories, and considered within the social-ecological system framework, the dissertation assesses the suitability of the governance framework to sustain GWS in high-groundwater-stress local contexts and provides governance reform recommendations.

Chapter 1 provides the theoretical background and analytical framing necessary to contextualize the three original manuscripts of the dissertation that are presented in *Chapters 2*, *3* and *4*. *Chapter 2* highlights multilevel governance gaps undermining groundwater security in vulnerable situations. *Chapter 3* collates reported cases of sub-watershed scale GWS vulnerabilities and conducts retrospective analysis to trace the origins of present-day groundwater governance weaknesses in the GLB. *Chapter 4* is a case study of the City of Guelph that applies statistical methods to confirm the causal relationship between governance and GWS. Given the City's unique governance approach, which has allowed it to maintain groundwater availability despite being wholly groundwater dependent and in a drought-prone region, the findings demonstrate the potential effectiveness of governance approaches featuring subsidiarity and

adaptiveness in addressing groundwater insecurity in similarly vulnerable communities. *Chapter 5* concludes the research, summarizing the dissertation's core contributions and recommending further research relevant to maintaining GWS. The dissertation closes with a meta-analysis of *Chapters 2*, *3* and *4* collating their main findings into a conceptual whole to propose a novel framework of good governance principles to better sustain GWS in the Basin's high-stress locales.

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My sincerest gratitude also goes to groundwater managers in the binational, federal, state/provincial and municipal institutions who provided data sets, gave feedback to questionnaires and participated in expert interviews throughout the duration of this study. Particular mention must be made of Mr. Scott Cousins from the City of Guelph’s Water Services Division for providing historical groundwater level and pumping data sets which laid the basis for many works in this dissertation and for providing feedback on one research chapter, greatly improving its accuracy. I am also particularly grateful to Mr. Howard Reeves of the United States Geological Survey, who provided valuable insights on groundwater vulnerability hotspots and trends throughout the GLB. I was fortunate to have near-100 percent response rates to the surveys I sent to state and provincial level groundwater management institutions and soil and water conservation districts on the US side of the Basin, as well as Ontario’s Conservation Authorities, in particular the Grand River Conservation Authority. Survey responses from these institutions were crucial to the provision of the rich body of empirical evidence for my research.

This research was made possible by the funding provided by the Natural Sciences and Engineering Research Council of Canada (NSERC). I am especially grateful for the NSERC’s CREATE Great Lakes training program, which I had the opportunity to participate in. Aimed at the next generation of scientists and policy-makers, the program provided foundational knowledge on the stressors and cumulative effects in the Great Lakes ecosystems and training on applicable research techniques to understand complex problems facing the Great Lakes.

Last but not least, I would like to acknowledge the McMaster Department of Earth, Environment and Society for facilitating my doctoral program as well as my fellow university student-colleagues for their help and advice. Finally, I would like to thank my family for their unending encouragement and support for the duration of my doctoral program.

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LIST OF ABBREVIATIONS

BWT	Boundary Water Treaty
CA	Conservation Authority
CAD	Canadian Dollar
CEC	Canadian Ecofiscal Commission
CGS	Canadian Geological Survey
COG	City of Guelph
CPR	Common Pool Resource
DEQ	Department Environmental Quality
DLTA	Draft Law of Transboundary Aquifers
DNR	Department of Natural Resources
DOI	Digital Object Identifier
ECCC	Environment and Climate Change Canada
EIA	Environmental Impact Assessment
GIN	Groundwater Information Network
GLB	Great Lakes Basin
GLC	Great Lakes Commission
GLEC	Great Lakes Executive Committee
GLSAB	Great Lakes Science Advisory Board to the International Joint Commission
GLWQA	Great Lakes Water Quality Agreement
GLSLCI	Great Lakes and St. Lawrence Cities Initiative
GLSWRA	Great Lakes Sustainable Water Resources Agreement
GRCA	Grand River Conservation Authority
GWS	Groundwater Storage
IJC	International Joint Council
IWRM	Integrated Water Resources Management
MDEQ	Michigan Department of Environmental Quality
MECP	Ministry of the Environment, Conservation and Parks of Ontario
MOECC	Ministry of the Environment and Climate Change
NAFTA	North American Free Trade Agreement
NOAA	National Oceanic and Atmospheric Agency
NSERC	Natural Sciences and Engineering Research Council of Canada
PGMN	Provincial Groundwater Monitoring Network
PTTW	Permit to Take Water
RO	Research Objective
SES	Social-Ecological System
SESDF	Social-Ecological System Diagnostic Framework
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNILC	United Nations International Law Commission
US	United States
USA	United States of America
USD	United States Dollar

USGS	United States Geological Survey
USMCA	United States–Mexico–Canada Trade Agreement
WRDA	Omnibus Water Resources Development Act
WWAT	Water Withdrawal Assessment Tool
MASL	Miles Above Sea Level
MGD	Million Gallons per Day

DECLARATION OF ACADEMIC ACHIEVEMENT

I, Khafi Weekes, declare that I conceptualized, designed and implemented the research contained in this dissertation with guidance and input from my doctoral program supervisor, Professor Gail Krantzberg. My thesis committee, including Dr. Dustin Garrick and Professor Jim Smith, provided comments on the thesis proposal, study protocols and research methodologies and instruments as well as on earlier drafts of this thesis.

In the School of Earth, Environment and Society, two forms of presentation of the doctoral dissertation are permitted: (i) a standard dissertation monograph, and (ii) a sandwich thesis option. The sandwich thesis option is centered on three or four chapters that consist of journal-type, original manuscripts that have been published or submitted for peer review in academic journals. These are considered core research chapters and are packaged with introductory and concluding chapters that assimilate the research agenda, main academic contributions, findings and implications of the research project, with the required results forming a conceptual whole. This dissertation is a sandwich thesis comprised of three original research papers (*Chapters 2–4*), an introduction (*Chapter 1*) and a conclusion (*Chapter 5*).

I confirm that I am the primary author of the manuscripts in my dissertation, and that the work was dominated by my intellectual efforts.

KHAFI WEEKES (Doctoral Student)

PREFACE

This is a sandwich thesis consisting of five chapters including an introduction, three research papers that have been published or submitted for peer review, and a conclusion. *Chapter 1* contains the background information needed to position the three main studies of the dissertation that are presented in *Chapters 2*, *3* and *4*. The dissertation's conclusion in *Chapter 5* summarizes the dissertation's core contributions, synthesizes the findings of the research chapters to propose a novel framework of good groundwater quantity governance principles and recommends future research directions to improve GWS governance in groundwater insecure GLB regions.

The first research paper contained in *Chapter 2* was published in June 2019 in the *Canadian Water Resources Journal*. It constitutes a gap assessment of water management policies from the binational to municipal government levels, identifying present-day governance weaknesses that can lead to groundwater quantity decline in high-use hotspots of the Basin. The second research paper is contained in *Chapter 3* was published in June 2021 in *Water*. It presents a baseline of reported cases of sub-watershed scale GWS vulnerabilities and conducts retrospective analysis tracing the origins of present-day GWS governance gaps. The third research paper is contained in *Chapter 4*. It was submitted to the *Environmental Science and Policy Journal* in April 2021. It consists of a case study of the City of Guelph, identifying the unique governance features that have enabled the City to maintain GWS levels despite growing climate and human use pressures, providing lessons relevant to reforming GWS governance in the GLB.

For each research paper, the dissertation author conducted research conceptualization, literature reviews, data collection, cleaning and analysis, and results interpretation; created visuals, images and tables; and prepared research paper drafts. Professor Krantzberg co-authored each paper, providing guidance on the development of research questions and approaches and critical review of research paper drafts in preparation for peer review. Ms. Maria Vizeu Pinheiro, an environmental attorney, co-authored the first research paper as she provided professional feedback on legal terms and international law processes governing groundwater use in international basins. The said three papers are as follows:

Chapter 2

Weekes, K., Krantzberg, G. and Vizeu, M. 2019. "Identifying Groundwater Sustainability Implications of Water Policy in High-Use Situations in the Laurentian Great Lakes Basin." *Canadian Water Resources Journal*, 44(4): 337–349. DOI:10.1080/07011784.2019.1623079.

Chapter 3

Weekes, K. and Krantzberg, G. (2021). "Twenty-first Century Science Calls for Twenty-first Century Groundwater Use Law: A Retrospective Analysis of Transboundary Governance and Future Implications in the Laurentian Great Lakes Basin." *Water*. 13(13):1768. DOI: 10.3390/w13131768.

Chapter 4

Weekes, K. and Krantzberg, G. (Submitted for Publication). "What Can We Learn About Improving Multilevel Groundwater Quantity Governance in the Laurentian Great Lakes Basin from the City of Guelph, Canada?" *Environmental Science and Policy*.

1. CHAPTER 1

INTRODUCTION

1.1. Thesis Aim

Despite being amongst the world's largest freshwater stores, the Laurentian Great Lakes Basin region is subject to mounting reports of groundwater storage (GWS) vulnerabilities across its drought-prone and groundwater-dependent communities (GLB; Reeves, 2011) that point to potential deficiencies in groundwater governance (Rivera, 2015; McKay, 2007; Morris *et al.*, 2003). To shed light on this issue, the overall aim of this dissertation is to assess the sufficiency of the governance framework to sustain sub-watershed scale groundwater quantities in high-groundwater-stress Basin locales. Research outcomes are intended to highlight gaps and features of the current governance framework that impact groundwater availability in these situations and inform recommendations to support the development of more robust policies, practices and institutions better suited to long-term groundwater quantity conservation in drought-prone and/or high-use locales.

For the purposes of this dissertation, the GLB groundwater quantity governance framework, or GWS governance framework, is defined as a multilevel arrangement of policies (in the form of official laws and guidelines), institutions and actors that set rules and governance processes to manage human uses, climate and other impacts on the long-term quantity of GWS. This dissertation evaluates the GWS governance framework from binational to municipal jurisdictions across the parts of the United States of America (US) and Canada within the 780,000 km^2 hydrological extent of the GLB (Granneman *et al.*, 2000) whose direct groundwater and surface water flow comprise a drainage basin that feeds the five Great Lakes. Analysis is geographically limited to the province of Ontario, eight US states (Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin), more than 120 First Nations and tribes (Jetoo and Krantzberg, 2014) and 263 municipal governments that are within the GLB's hydrological boundary. Analysis of governance in the province of Quebec is not part of the research scope, as although the province partners with the GLB states/province in water governance, its lands drain into the St. Lawrence River Basin, which is downstream of and distinct from the GLB.

This is a sandwich thesis, including an introductory chapter, three core research papers contained in *Chapters 2–4* that have been peer reviewed and published or submitted for peer review, and a conclusion chapter. This introductory chapter does not include a standalone literature review as this is instead included in each of the three research papers. To provide adequate theoretical background and to frame the overall logic of the analytical approach, this Chapter proceeds with a description of the research context and problem rationale. In so doing, it outlines the typical challenges of groundwater quantity governance in international basins that can undermine GWS sustainability. It then reviews theories on transboundary governance process reform that better support GWS sustainability in water-rich regions such as the GLB. It then presents the empirical context of the dissertation, introducing the GLB's emerging GWS vulnerability problem as well as relevant GWS stressors (climate, groundwater use and governance factors) that are considered throughout the dissertation. Research questions and key academic contributions are then summarized, followed by a summary of the overall analytical approach of this body of research. The Chapter concludes with an overview of the thesis organization, including a summary of the contents of *Chapters 2–4*.

1.2. Research Context and Problem Rationale

1.2.1. Drivers and processes of GWS depletion in international basins

Groundwater accounts for a third of global unfrozen, freshwater resources, providing 50 percent of drinking water and the main source of water for major industries, especially in the agricultural sector (UN-IGRAC, 2020). Human demands for groundwater resources have been exponentially increasing as for each of the past 50 years, the global demand for groundwater has doubled (Wada and Heinrich, 2012). The changing climate is also altering weather patterns, increasing the intensity and frequency of droughts in some parts of the world (IPCC, 2014).

These stressors have negative implications for maintaining GWS volumes, as when the resource is pumped at a rate higher than its recharge without consequence on aquifer storage and surface waters, over time, this can lead to long-term depletion of its quantities (Van Camp, Radfar and Walraevens, 2010). UNESCO defines an overdeveloped aquifer as having "prolonged (multi-annual) withdrawal of groundwater in quantities exceeding its average annual replenishment, bringing about a persistent fall in groundwater levels and reduction of aquifer reserves with undesirable side effects" (Foster and Loucks, 2006). These undesirable side effects indicate GWS vulnerability and include long-term reduction in stream baseflow, land subsidence, upwelling of brines and loss of groundwater-dependent ecosystems. With increasing reports of these indicators throughout the world's now 366 identified transboundary aquifers (UN-IGRAC, 2020), roughly one third of international basins have been assessed as currently experiencing groundwater storage distress (Wada and Heinrich, 2012).

GWS is particularly sensitive to fluctuations in human use rates and changes in precipitation patterns due to its status as a common pool resource (Ostrom *et al.*, 2007). The first panel on the study of common pool resources (CPRs) in Annapolis, USA in 1985 articulated defining characteristics of CPRs as including a defined renewability rate and subtractability of resource units with extraction and/or "sinking" of pollutants (Thompson, Feeny and Oakerson, 1986). In this context, groundwater can be thought of as containing a finite set of resource units (volume of stored groundwater in aquifers) that is maintained by a physical-environmentally determined rate of inflow (natural recharge) and outflows (natural discharge to surface water bodies). This natural equilibrium for maintaining GWS can be easily disrupted by human overuse that reduces environmental flows or climate impacts that can deplete natural recharge.

1.2.2. Characterizing sustainable groundwater quantity governance challenges in international basins

Vulnerabilities in groundwater quantity are often related to problems of governance (OECD, 2017). This stems from inherent challenges in CPR governance, as articulated in the 1985 Annapolis conference as: the high cost of preventing access by potential users (free riders) unless they agree to abide by a set of rules; the presence of a heterogeneity of actors, users and institutions that govern the use of the resource increasing with scale; the presence of institutions and rules in CPR governance frameworks to combat free riding and unsustainable use by defining "who has access to a resource, what can be harvested from, dumped into, or engineered within a resource, and who participates in key decisions about these issues and about transferring rights and duties to others" (Ostrom *et al*., 2002). Involving planning, coordinating, policy-making, implementation and monitoring of policy outcomes (Newell *et al.*, 2012), governance provides the means by which groundwater use may be managed and environmental stressors on GWS addressed.

As described by Cash *et al.* (2006), in international basins, these governance processes occur across scales ("the spatial, temporal, quantitative or analytical dimensions used to measure and study a phenomenon") and levels ("the units of analysis that are located at different positions on a scale”). For the governance of groundwater in international basins, spatial scale is of utmost importance, with the watershed scale widely considered optimal (Cooley and Gleick, 2011). This is because, given the wide-ranging physical-environmental settings across the spatial extent of international basins, watersheds provide the physical-environmental boundary within which natural factors that control GWS are contained, which is conducive to effective governance (Mollinga, 2010). Watersheds are also ideal as they can be further discretized to smaller scales or sub-basins, facilitating governance of location-specific groundwater issues (Expert Panel on Groundwater, 2010).

The jurisdictional scale is also important as it refers to how the authority to make groundwater use decisions is disseminated. As jurisdictional scales intersect watershed boundaries in international basins, groundwater flow systems are transboundary (Holley *et al*., 2012), allowing riparian states to have shared rights to use the resource. As such, governing for sustainable access to transboundary groundwater resources involves inter-jurisdictional agreements, policies, institutions, monitoring and decision-making underpinned by intra- and intergovernmental collaboration and cooperation (Richey *et al.*, 2015; Cosens, 2010). In international basins that are shared by two or more federalized riparian states, literature recognizes that water governance takes place at multiple levels (Garrick *et al.*, 2013; Suhardiman and Giordano, 2014) as jurisdictional scales can be further broken down into levels—from the binational to municipal levels of government—within which a wide range of governmental and non-governmental institutions and actors are accorded different water governance roles and responsibilities as per *Table 1*.

Table 1: Typical Water Governance Roles and Responsibilities in Federalized Riparian States (*Source: Suhardiman and Giordano, 2012*)

GOVERNMENT LEVEL	GEOGRAPHIC SCALE	GOVERNANCE ROLES AND RESPONSIBILITIES
INTERNATIONAL	Basin-wide	- Intergovernmental agreements. - International groundwater use conflict resolution.
FEDERAL	Regional - sub-Basins	- National legislation of intergovernmental agreements. - Transboundary groundwater use conflict resolution within national territory. - Intra-governmental delegation of authority to multiple, territorially-based levels of government. - Broad oversight of multilevel non-governmental and governmental actors and institutions involved in water governance and management.
STATE	Regional - multiple watersheds	- Regional-scale land use planning, permitting, policy development, conflict resolution, coordination and monitoring.
MUNICIPAL	Local - </= one (1) or more watersheds	- Local-scale land use planning, policy development (e.g., municipal bylaws), research and monitoring.

Effectively carrying out these groundwater governance roles and responsibilities in federalized riparian states is complex, requiring efficient coordination, cooperation and conflict resolution between multilevel governments and across environmental scales, both within and between federalized riparian states (Eliasson, 2015; Zeitoun *et al.*, 2011). These governance processes are often fraught with issues of power dynamics, institutional fragmentation, sovereignty, competing values for and uses of the resource as well as differing socio-environmental needs, contexts and conditions that can challenge sustainable groundwater governance (Armitage *et al.*, 2015). Of these, power dynamics are the central issue that controls the extent to which groundwater quantity governance can be sustainable (Newell, 2012). This is because, power—defined as the capacity to inhibit or make change to achieve preferable outcomes (Sayer, 2012)—in the context of natural resource governance determines "who has access to a resource, what can be harvested from, dumped into, or engineered within a resource, and who participates in key decisions about these issues and about transferring rights and duties to others" (Ostrom *et al*., 2002).

In international basins, power can be distributed inequitably (Zeitoun *et al.*, 2011), creating asymmetries in power dynamics and water conflicts between riparian states (Eliasson, 2015). Asymmetries often stem from the unique arrangements of institutions and division of authority between governance levels in each federal riparian state, with states having their own governance capacities and processes to carry out in key GWS governance activities (Suhardiman and Giordano, 2012). Riparian states also generally have differences in arrangements for cooperating and collaborating with non-governmental actors and institutions (e.g., environmental NGOs and academic stakeholders), which can impact the extent to which they are included in governance (Suhardiman and Giordano, 2014; McIntyre, 2010). Outcomes of these asymmetries often include institutional and policy fragmentation, policy gaps and/or overlaps, non-transparent governance processes and inequity in access to shared groundwater resources (Delli Priscoli and Wolf, 2009), all of which are hallmarks of unsustainable governance (Lockwood *et al.*, 2010).

Sustainable transboundary groundwater governance challenges are further nuanced in "hydrocracies": large-scale, multi-layered hydraulic/water bureaucracies (Molle, Mollinga and Wester, 2009). Since their inception, hydrocracies have addressed water resource sustainability challenges through the execution of conspicuous, major engineering schemes such as mega-dam projects, with relatively less focus on "soft" governance approaches through enhanced policy and institutional actions (Molle, Mollinga and Wester, 2009). Moreover, when "soft" water governance approaches are employed, a top-down approach is characteristic with higher government (typically federal and state) having broad, regional oversight and mandates covering the majority of groundwater governance roles and responsibilities. Herein, rigid approaches to policy and decision-making dominate, even when they conflict with contemporary socio-environmental needs, frequently resulting in unsustainable resource outcomes (Williams, 2020).

In water-abundant hydrocracies such as the GLB, given the wider, regional-scale purview of higher levels of government that have the lion's share of water governance authority, localized, sub-watershed scale unsustainable water outcomes are often overlooked or inadequately considered. In so doing, higher-level governments often fall short in effectively monitoring, developing policies and making decisions applicable to widely varying and complex local needs and conditions, or being sufficiently flexible to respond to location-specific groundwater security threats (Cooley and Gleick, 2011). Bolstered by the fact that long-term declines in water levels are not generally observed at the Basin-wide scale, as intra-Basin water diversions and regional differences in water use intensities are not reflected in Basin-wide water balance accounting (Swaffer, 2020), a false, widespread perception of water abundance is typically created (Bakker and Cook, 2011). As the local scale is where most water vulnerabilities occur, this governance approach often leads to sub-watershed scale water resource depletion.

The above phenomenon has been described in literature as the panacea problem (Ostrom and Cox, 2010; Ostrom, 2009; Ostrom, Janssen and Anderies, 2007) wherein overly simple, blueprint governance solutions are applied to solve widely ranging natural resource problems. In what is also called the "blueprint approach", governments may fail to properly govern resources by homogenizing the diversity of environmental and socio-political settings within their jurisdictions. This leads to a lack of fit between governance frameworks and their supposed social-environmental targets. As such, the predominant top-down, blueprint governance approach of hydrocracies risks stymieing innovations and reforms needed to better conserve water uses and address location-specific environmental stressors to water availability (Williams, 2020).

1.2.3. Contending with sustainable groundwater quantity governance challenges in federalized, international basins: key solutions and concepts

Recognizing that rigid blueprint, top-down approaches to governance can undermine GWS sustainability in international basin hydrocracies, the literature has identified adaptive governance as key to the long-term maintenance of GWS in these settings (Falkenmark and Jägerskog, 2010; Korten, 1980). Acknowledging the non-stationarity of water resources as well as changeful local socio-environmental needs and conditions (Milly *et al.*, 2008), adaptive governance approaches explicitly consider natural resource systems as complex and characterized by being in a constant state of flux, non-linearity and uncertainty (Folke *et al.*, 2005). In order to result in sustainable natural resource outcomes, adaptive governance encourages the augmenting of institutional capacities and governance processes to adapt to change.

Subsidiarity is key to adaptive governance. Defined as the organizing principle of devolving greater governance responsibilities and roles to the lowest and least-centralized government level with sufficient political authority and capacity, subsidiarity can better convey local-scale problems and sustainability concerns in multilevel governance. Moreover, when there is potential for a government level to overcome an existing capacity deficit, the subsidiarity principle implies a duty of higher-level governments to provide necessary support to help realize that potential (Marshall, 2007). The process typically enables the establishment of: (i) processes and institutions that are flexible, promote data sharing and iterative learning amongst multilevel governments and non-governmental stakeholders (Dietz *et al.*, 2003); (ii) mechanisms for governance, particularly in higher levels, to improve decision- and policy-making through increased awareness of local water resource concerns, needs and socio-environmental conditions (Green *et al.*, 2013); and (iii) investments to build capacities in local levels of government, particularly watershed management organizations (WMOs) and municipal-level institutions

(Marshall, 2007) that are generally excluded from key aspects of transboundary groundwater governance in federalized, riparian states as per *Table 1*.

Key to successfully mainstreaming subsidiarity and adaptive governance is the inclusion of municipal governments and WMOs, as they can be well-positioned with adequate levels of funding, technical staffing and authority to initiate consideration of local needs and social-environmental concerns in multilevel water resource governance (Green *et al.*, 2013; De Stefano *et al.*, 2012; Cooley and Gleick, 2011). Municipal-level institutions are closer in scale to localized water vulnerability issues and are staffed by locals with vested interest in sustaining groundwater availability. WMOs are also key because they operate within the natural boundaries of watersheds (Huitema and Meijerink, 2014) and can play key roles in conducting research, monitoring and coordinating responses to address sub-watershed scale water problems (Cooley and Gleick, 2011).

The literature documents the potential benefits of deepening the involvement of municipal institutions and WMOs in transboundary groundwater governance including the (i) creation and enabling of sub-watershed scale scientific information exchange between jurisdictions on groundwater availability, environmental settings and stressors that help to inform policy responses and decisions (Muys *et al.*, 2007); (ii) boosting of iterative governance, creating science-policy feedback loops through their ability to monitor the impacts of local-level implementation and enforcement of international agreements and federal-state level policies and decisions impacting GWS (De Stefano *et al.*, 2012); and (iii) up-scaling of community perspectives with greater inclusion of bottom-up perspectives (i.e., local societal needs and conditions) in multilevel policies and decision-making impacting GWS (Green *et al.*, 2013). As such, the extent to which municipal and watershed-scale institutions are integrated in transboundary groundwater quantity governance processes can determine the degree of adaptability and flexibility of multilevel responses to emerging GWS challenges, key attributes that can promote sustainable groundwater governance in international basins (Akamani and Wilson, 2011; Raadgever *et al*., 2008).

As such, this body of research consists of power-based analysis of the institutions, policies and processes that comprise the groundwater quantity governance framework of the GLB hydrocracy; highlighting the GWS governance gaps, interests advanced and GWS sustainability outcomes achieved in GLB sub-watersheds where groundwater security vulnerabilities are occurring. To do this requires a comprehensive understanding of the multilevel (i) policies; (ii) governance processes (e.g., intergovernmental partnerships and agreements and intra-governmental resource use decisions); and (iii) roles and functions of institutions and key stakeholders, (e.g., policy-making, scientific data creation and sharing, resource use decision-making, coordinating, cooperation and monitoring) between and across binational to municipal government levels in the jurisdictions of the US and Canada that lie within the Basin.

In so doing, the findings can provide important empirical and theoretical insights useful to assessing the extent to which the multilevel governance framework contributes to sustaining GWS in high-stress situations, specifically in addressing groundwater overuse, climate change and other compounding pressures that can result in GWS decline. Taking into consideration the core principles of adaptive governance and subsidiarity, the findings can inform proposals for reforms to the existing groundwater quantity governance framework that are tailored to the unique social and environmental conditions of high-stress hotspots of the Basin to improve GWS sustainability.

1.3. Empirical Context: The Laurentian Great Lakes Basin

1.3.1. Current situation of sub-watershed scale groundwater storage and sustainability

The GLB stores 22,671 km^3 of freshwater, of which roughly one fifth is stored in the form of groundwater (Granneman *et al.*, 2000). Though estimates of Basin-wide GWS range from 5,585 km^3 to 4,000 km^3 (Coon and Sheets, 2006), at the sub-watershed scale, mounting human and climate pressures are increasingly threatening the long-term quantity of GWS in aquifers supplying communities and industries reliant on the resource.

Human pressures on GWS stem from groundwater steadily becoming an important resource to the US $6 trillion regional GLB economy (Kavcic, 2016). As of 1998, the total withdrawal of groundwater in the GLB was estimated at 2.3 km^3/year (Reeves and Granneman, 2005; Solley *et al.*, 1998). Currently 58.4 km^3/year of groundwater is withdrawn across the Basin, of which the total consumption of groundwater is estimated at 5.8 km^3/year (GLC, 2016); groundwater consumption being defined as pumped groundwater that is not returned to original source aquifers that is often permanently lost from the Basin embedded in products and exported goods. Increasing demand is driven by the growing population of the "Great Lakes Megalopolis" as public policy since the 1980s has rebranded the former Rust Belt as an aspirational region (Kotkin and Schill, 2013). Drawn by emerging R&D industries, the knowledge economy and comparatively low housing prices, the GLB population is expected to increase by 8 percent by 2025 concentrated in specific locales (Lang and Dhavale, 2005).

While groundwater demand has been rising, natural recharge has been decreasing in many parts of the Basin. Growing human settlements are increasing impermeable zones, reducing natural recharge (Cohen, 2009). Groundwater demand has also been unequal throughout the Basin as there are significant differences in the populations and groundwater uses, and their use intensity across the thousands of communities in the GLB states/provinces. As well, the impacts of climate change are expected to induce temporal seasonal extremes that could further intensify droughts (Lofgren, Hunter and Wilbarger, 2011). Climate change will increase precipitation while concentrating most of it within winter months when the ground is frozen and infiltration is reduced. In these conditions, recharge of GLB aquifers is expected to decrease by up to 20 percent (Hall and Stunz, 2008).

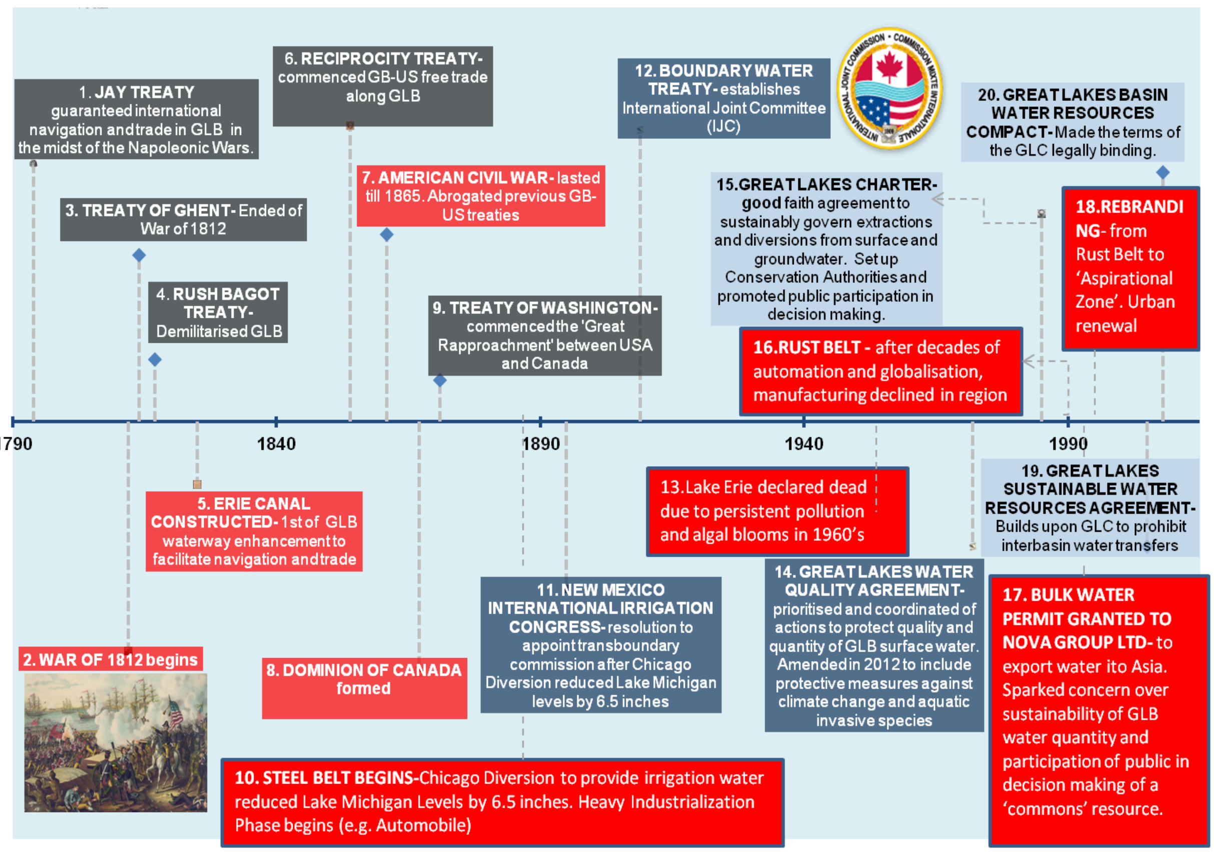
Though the full extent of groundwater insecurity is poorly understood throughout the Basin and not comprehensively monitored (Kornelsen and Coulibaly, 2014), groundwater management institutions and researchers are increasingly reporting GWS vulnerability indicators (Rivera, 2015; Kornelsen and Coulibaly, 2014). While GWS insecurity is not widely reported throughout the GLB, the Basin has been recently characterized as having a high risk of GWS shortages developing at the sub-watershed scale in high-groundwater-use and/or drought-prone locales (Reeves, 2011).

1.3.2. Groundwater quantity governance in the GLB

The control of groundwater use within international basins has almost always been subsumed within international treaties and agreements devised for regulating surface water use and/or aimed at preserving surface water quantities. Before World War II, treaties and agreements that mentioned groundwater addressed it as an international border issue. It was not until the 1950s, with increasing recognition of the importance of groundwater as a resource, that the terms "aquifer" and "groundwater" were used. However, these were usually included in international treaties or agreements as a measure to maintain long-term and equitable access to surface water resources by riparian states (Martinez and Santos, 2005).

The same can be said of transboundary water governance in the GLB. Binational treaties and agreements were initially focused on preserving the navigability of the Basin's surface waters straddling the international border for war campaigns, and later for the preservation of commerce and trade (*Figure 1*).

Figure 1: Key phases in the transition towards groundwater quantity governance in the Great Lakes Basin (*Source: author's compilation*)



1	FOCUS ON FACILITATING FREE INTERNATIONAL NAVIGATION AND TRADE
2	FOCUS ON MAINTENANCE OF SURFACE WATER QUANTITY AND/OR QUALITY
3	FOCUS ON MAINTENANCE OF SURFACE AND GROUNDWATER QUALITY AND/OR QUANTITY
4	PIVOTAL SOCIAL, ECONOMIC OR POLITICAL EVENT

It was not until 1956 with the passage of the first *Great Lakes Compact* that transboundary water use governance stopped being treated as an international border issue, heralding the adoption of a whole-of-Basin approach. However, even then, groundwater was not included within the *Compact*'s scope. This changed in 1985 when the *Great Lakes Charter* was signed and for the first time mentioned groundwaters within its scope. However, there were no unique measures to govern groundwater use based on physical-environmental sustainability limits of aquifers to maintain GWS, reinforced by the explicit statement that the overall goal of the *Charter* was to protect GLB surface water quantities. To this day, these governance weaknesses have remained a feature of successive binational agreements between the US and Canada governing the uses of GLB freshwaters.

Recent developments in transboundary groundwater quantity governance reflect these same weaknesses. Currently, there are more than 400 international treaties and agreements related to the governance of transboundary freshwater use, of which approximately 100 mention groundwater (Sindico, 2020). Typically corresponding to regions that have significant surface water degradation and long-standing problems with surface water availability, the vast majority of treaties mentioning groundwater are from Europe with 35 treaties, followed by Africa, then Asia and then North America with 4 treaties. Of these, most mention groundwater as a means to protect surface water, with the vast minority having specific groundwater governance prescriptions including extraction limits, allocation and science-based management principles (Martinez and Santos, 2005; Sindico, 2020).

Put into the wider context of the international governance of the quantity of transboundary groundwater resources, the GLB's successive treaties and agreements fall into the relatively progressive category. Unlike most regions that mention groundwater in the scope of transboundary treaties and agreements, the GLB is a relatively water-rich region. However, similar to these areas, its treaties and agreements do not include specific groundwater use guidelines that are different from those used for surface water. This has contributed to the failure of emerging threats to sustaining GWS to reach the forefront of the GLB water governance agenda. Policy prescriptions in the *2005 Great Lakes - St. Lawrence Basin Sustainable Water Resources Agreement* (*2005*

GLSWRA), the most recent binational agreement governing GLB water use, were shortly thereafter included in GLB federal and state/provincial government legislation, including GWS governance gaps (Karkkainen, 2013; Kreutzwiser, Durley and Priddle, 2013). In addition, multilevel governments themselves have largely excluded groundwater resources from their public trust responsibilities (Kilbert, 2010), focusing instead on the preservation of surface waters in their other statutes, court decisions and non-legally binding regulations. One well-known example is the recent Ohio constitutional amendment (Ohio Const. Art. I, § 19b.) made in response to concerns about the enshrinement of *2005 GLSWRA* policies into state law. The amendment specified, *inter alia*, that landowners have property rights to non-navigable waters and groundwater in Ohio and that such waters are not subject to the public trust doctrine, thereby precluding GWS sustainability concerns from being prioritized in laws aimed at preserving GLB water resources.

The result of this groundwater quantity governance blind spot in the world's international treaties and agreements is that for each of the past 50 years, global demand for groundwater has doubled, leading one third of international basins to currently experience GWS distress as a consequence (Wada and Heinrich, 2012). Similarly, in the GLB, while surface water consumption decreased by 15 percent between 1995 to 2005, groundwater consumption increased by 3 percent in the same period largely due to increased withdrawals for public water supply and the agricultural sector (Pentland and Mayer, 2015). As this has been concentrated in high-use hotspots, sub-watershed scale cases of long-term GWS decline are being increasingly reported across the Basin (Reeves, 2011; Howard and Gerber, 2018; Weekes, Krantzberg and Vizeu, 2019). Climate change is intensifying these GWS decline impacts.

Considered with the inherent CPR traits of groundwater, rising human and climate pressures that are unequally distributed across the Basin's watersheds and the lesser availability of

GLB groundwater compared to surface waters, the current approach to groundwater quantity governance is increasingly unsustainable. There is a need to address the long-term water security concerns of residents and industries in drought-prone and/or groundwater-reliant locales and proactively establish governance measures to prevent further proliferation of groundwater insecurity across the Basin's communities.

1.4. Specific Research Objectives and Academic Contributions

Mitigating the impacts of emerging GWS threats in high-stress locales requires reform of the multilevel governance framework and relevant binational agreements. This proposition justifies the overall objective of this dissertation whereby, in order to make informed recommendations for GWS governance reform, the degree to which the groundwater quantity governance framework addresses the unsustainable groundwater uses and climate impacts that drive GWS decline must be assessed. Expanded into four specific research objectives, this dissertation will:

I. Conduct a gap assessment of critical policies, governance processes and the roles of key institutions and stakeholders between and across binational to municipal government levels that can lead to groundwater quantity decline in aquifers supplying high-stress locales of the Basin;

II. Develop a baseline of empirical evidence of GWS governance outcomes with a comprehensive collation of reported cases of persistent GWS decline in the GLB;

III. Demonstrate the utility of integrating subsidiarity in multilevel governance for improving the sustainability of GWS in high-stress locales; and

IV. Propose good governance principles for a reformed groundwater quantity governance framework that addresses climate risks and growing groundwater demand in order to better sustain GLB groundwater quantity in vulnerable locations of the Basin.

These research objectives and their original academic contributions are addressed in *Chapters 2–4*. The overall original contributions of this dissertation, specific contributions of each research objective and linkages to their corresponding chapters are summarized below in *Table 2*.

Table 2: Research Objectives, Corresponding Chapters and Original Academic Contributions

Research Objective	**Chap(s)**	**Academic Contribution of Each Research Objective**	**Overall Academic Contribution**
Conduct a gap assessment of critical policies, governance processes and the roles of key institutions and stakeholders between and across binational to municipal government levels that can lead to groundwater quantity decline in aquifers supplying high-stress locales of the Basin.	Two Three	Identification and description of the features of the present-day governance framework that can constrain and enable sustainable GWS governance in high-use situations. Identification of the persistent gaps and weaknesses that have led to current weaknesses in the governance framework, tracing the 100+ year evolution of modern water governance in the GLB. Updating of the literature on power dynamics involved in water quantity governance in the GLB, adding a lesser-investigated theme with the focus on groundwater.	1. Identification of multilevel governance gaps in the existing groundwater quantity governance framework that should be modified to better sustain groundwater storage in high-use and/or drought-prone settings. 2. Proposal of an optimized groundwater quantity governance framework designed to better address risks to GWS that can be widely applicable to maintain GWS in high-stress situations across
Develop a baseline of empirical evidence of GWS governance outcomes with a comprehensive collation of reported cases of persistent GWS decline in the GLB.	Two Three	Deepened understanding of the range of social-environmental drivers of GWS decline (e.g., land subsidence, baseflow reduction, lowered groundwater table levels, loss of groundwater-dependent habitats, etc.) and how they are manifested in cases of persistent GWS decline across the GLB. Increased understanding of the Basin-scale to sub-watershed scale occurrences of persistent GWS decline that need to be considered for	

		comprehensive multilevel GWS governance reform.	the parts of the GLB states and Ontario that are within the Basin.
Demonstrate the utility of integrating subsidiarity in multilevel governance for improving the sustainability of GWS in high-stress locales.	Four	Identification of GLB-relevant opportunities and strategies for integrating local and watershed scale institutions in multilevel policy and decision-making to improve the sustainability of groundwater availability in high-stress situations.	
Propose good governance principles for a reformed groundwater quantity governance framework that addresses climate risks and growing groundwater demand in order to better sustain GLB groundwater quantity in vulnerable locations of the Basin.	Five	Proposal of a framework of good GWS governance principles broadly applicable the range of social-environmental contexts where GWS vulnerabilities occur across the Basin.	

The specific contributions of each *Research Objective* are further detailed below.

I. To conduct a gap assessment of critical policies, governance processes and the roles of key institutions and stakeholders between and across binational to municipal government levels that can lead to groundwater quantity decline in aquifers supplying high-stress locales of the Basin

The contribution of this objective is twofold. The first is the identification of the features of the present-day governance framework that can constrain and enable sustainable GWS governance in high-use situations. The second is the understanding of historical gaps and governance patterns that have led to current governance outcomes and groundwater insecurity across the Basin.

Given that analysis is systematically done from the binational to municipal governance levels, the findings update the literature on power dynamics involved in GWS governance in the GLB. The last comprehensive assessment of this kind was published in a 2000 law review (Saunders, 2000), prior to the adoption of the *2005 GLSWRA*, the subsequent amendments of multilevel laws and regulations and the creation of new GWS governance institutions in the past

15 years across the GLB states/province, which collectively constitute the present-day GWS governance framework. In addition, the findings of the historical analysis of the evolution of GWS governance in the Basin add a unique dimension to the study of power dynamics controlling transboundary water use. These studies have overwhelmingly focused on the evolution of the governance of the Basin's surface water resource quantities, with far fewer studies specifically documenting historical GLB groundwater governance.

Finally, the findings also provide the foundation for the rest of the research as they indicate the main governance features and long-standing pathologies that may need further evaluation to glean better theoretical and empirical insights into the sufficiency of GWS governance. Moreover, these insights provide for well-informed recommendations of approaches to improve multilevel GWS governance, lessons that form part of the novel framework of good governance principles proffered in *Research Objective IV*.

II. To develop a baseline of empirical evidence of the state of GWS decline in the GLB

Multilevel GLB governments have recognized the need to continue to invest in groundwater quantity research to fill critical knowledge gaps in groundwater use and availability in order to better target policies and decision-making (Granneman and Van Stempvoort, 2016). However, they face two main challenges. The first is that they lack a shared database with consistent methods and metrics tracking GLB groundwater use. The current Regional Water Use Database does not disaggregate data set categories to specifically track groundwater use. With GWS monitoring done across the eight US states and the province of Ontario, federal institutions such as the United States Geological Survey and Canadian Geological Survey, as well as state/provincial monitoring networks and GWS governance institutions, there are multiple GWS use and availability data sets with inconsistent methods for estimating GWS information. Moreover, while Basin-wide, long-term GWS trend estimations can be done via satellite readings, these readings have wide margins of error and their resolution is insufficient to capture highly localized GWS shortage developments (Huang *et al.*, 2010). As such, a comprehensive and consistent measure of GWS use and decline has not yet been created, challenging sustainable GWS governance and science-based decision-making on groundwater use. The second challenge is that at the sub-Basin to sub-watershed scale, GWS estimations are mainly based on groundwater table levels in observation well networks that do not yet comprehensively cover the Basin's groundwater flow systems (Kornelsen and Coulibaly, 2014). This monitoring approach may be ignoring other important indicators of GWS decline, providing only a partial picture of GWS availability and seasonal groundwater flow changes in drought-prone and/or groundwater-reliant areas that need higher quality information on which to base groundwater use decisions.

As such, the main contribution of this objective is to collate current reports of cases of GWS decline from the Basin to the sub-watershed scale of the GLB, using the full range of relevant GWS decline indicators. While GWS availability is typically tracked using groundwater table levels, other environmental indicators are covered to achieve this *Research Objective* to capture a more complete snapshot of the state of GWS decline across the GLB. Reports consider land subsidence, loss of dependent ecosystems, upwelling of heavy metals and brines and reduced stream baseflow resulting from long-term groundwater pumping.

These findings compliment *Research Objective I*, as they provide insight into GWS governance outcomes, shedding light on the range of settings and situations in which they are failing to prevent GWS decline occurrences in the Basin. Moreover, as the findings illuminate more clearly how widespread cases of persistent GWS decline are occurring and their associated socio-environmental conditions, this informs the proposal of highly relevant governance reforms.

III. To demonstrate the utility of integrating subsidiarity in multilevel governance for improving the sustainability of GWS in high-stress locales

In the context of the GLB, subsidiarity involves devolving greater governance authority to lower levels of government and WMOs with sufficient capacity and authority to carry out these roles and responsibilities. Thus, *Research Objective III* demonstrates the utility of subsidiarity through a case study involving statistical evaluation of the causal relationship between governance and long-term GWS in the City of Guelph, a municipality in the Ontario sub-Basin of the GLB. The City is distinguished by its direct involvement in and science-based policies and decision-making standards impacting GWS governance as well as its close monitoring and provision of incentives to ensure that residents adhere to GWS governance prescriptions. It is also unique in its close collaboration with the Grand River Conservation Authority, the local WMO that monitors and conducts research on GWS in the sub-basin in which the City lies, allowing for science-based groundwater use governance. The City has managed to maintain relatively stable GWS levels despite being entirely groundwater dependent, having rising groundwater demands and increasingly experiencing drought conditions. This research seeks to determine the degree to which its governance approach has contributed to these positive GWS outcomes.

The findings add to the body of empirical evidence demonstrating that the practice of top-down GWS governance that largely omits local institutions from the critical GWS governance roles of policy- and decision-making affecting the terms of their own local-level groundwater use can reduce prospects for GWS sustainability (Williams, 2020; Falkenmark and Jägerskog, 2010; Muys *et al.*, 2007; Morris *et al.*, 2003), particularly in high-stress locales in the GLB. Drawing lessons from the case study, opportunities for mainstreaming subsidiarity and adaptive governance by leveraging the scale and capacity of local institutions to address localized groundwater quantity stressors are proposed.

IV. To propose good governance principles for a reformed groundwater quantity governance framework that addresses climate risks and growing groundwater demand in order to better sustain GLB groundwater quantity in vulnerable locations of the Basin

Whereas the research outcomes of *Research Objectives I*, *II* and *III* provide empirical evidence of multilevel governance gaps and their unsustainable GWS outcomes in high-stress locales, this objective advances proposals to improve sustainable groundwater quantity governance. Collating the recommendations and lessons gathered from the previous *Research Objectives* into a conceptual whole, the original contribution of *Research Objective IV* is to develop a framework of good governance principles that can be useful in improving GWS sustainability in high-use and/or drought-prone regions of the GLB.

1.5. General Analytical Approach

As discussed previously, water-rich international basin hydrocracies such as the GLB can be prone to panacea problems, overlooking complex and diverse sub-watershed scale GWS vulnerabilities in their blueprint, top-down approaches to governing groundwater resources (Williams, 2020; Ostrom and Cox, 2010). Adaptive governance and subsidiarity have been identified as means to address these governance problems, given their capacity to increase the participation of local institutions in multilevel governance processes (Rijswick and Wouters, 2015; Falkenmark and Jägerskog, 2010). The benefits of including local institutions have also been widely acknowledged as including their ability to increase the heterogeneity of location-specific data, perspectives and interests served, allowing for greater feedback and iteration of multilevel governance approaches that explicitly consider the complex local impacts of GWS governance (Akamani and Wilson, 2011; Raadgever *et al.*, 2008). Therefore, ascertaining the extent to which (i) adaptive governance and subsidiarity have been mainstreamed and (ii) a hydrogeological sustainability science-based understanding of the complex local physical-environmental conditions impacting GWS informs multilevel governance processes, and the cumulative effect on GWS in high-stress locales, is key to evaluating the degree to which the governance framework is effective in sustaining groundwater quantities in high-stress sub-watersheds in the GLB.

On this basis, it can be useful to consider the GLB as embedded within a social-ecological system (SES). SESs are characterized as the bio-geophysical units and associated actors that use and govern natural resource systems, as complex and adaptive and as delimited by spatial or functional boundaries (Ostrom *et al.*, 2002). Considering the GLB as an SES, assessments of the governance framework capacity to sustain GWS in high-stress sub-watersheds must contend with three forms of complexity identified by Mollinga (2010): (i) "ontological complexity" that is based on the premise that the GLB consists of heterogeneous human and environmental attributes connected by various multi-scale and multilevel linkages that often have non-linear and unintended consequences on GWS; (ii) "societal complexity" stemming from the fact that groundwater resources are used by a diverse set of users with competing interests, values and purposes; and (iii) "analytical complexity" arising from the highly disciplinary evolution of science which makes any single disciplinary approach inappropriate to comprehensively assess the GWS governance framework. To do so, Ostrom *et al.* (2007) advised that "one needs to build on the work of scholars who have undertaken careful, well documented and theoretically sound studies of ecological systems, socioeconomic systems, and linked SESs. We should stop striving for simple answers to solve complex problems."

1.5.1. Overall analytical framework

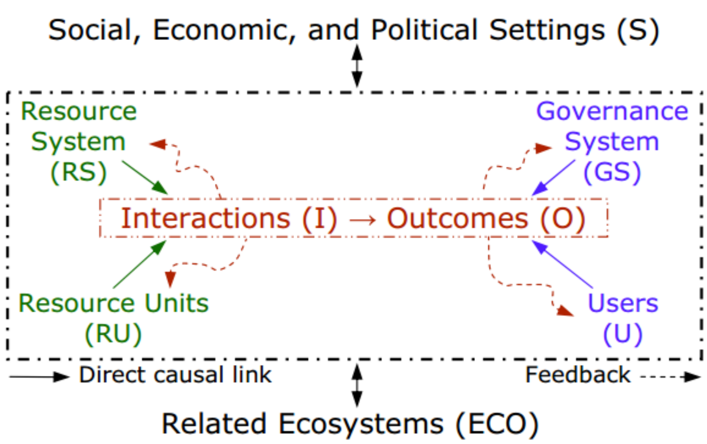
Given the thematic diversity of the types of linkages between human and environmental systems in the GLB SES, a singular discipline or school of thought will be insufficient to properly assess the diverse range of governance–groundwater interactions and feedbacks that impact GWS sustainability in high-stress locales. To tackle these complexities, "critical multiplism" (Ostrom *et al.*, 2002)—the application of theories, perspectives and methods from contrasting disciplines—is required to evaluate the governance features that can cause groundwater resource problems. As such, the selection of an appropriate analytical framework—a bounding group of general elements and their common relationships that must be considered when undertaking analysis of phenomena—that allows for the inclusion of this range of analysis is paramount.

More than three dozen analytical frameworks have been developed to date to analyze complex SESs. To select the most appropriate analytical framework, criteria developed by Binder *et al.* (2013)—who compared 10 frameworks commonly used to assess complex human ecological systems—were applied. These criteria specify that the ideal framework should: build from a pre-existing framework, have been tested and supported by findings from a body of rigorous academic research, include the typical variables that comprise SESs, provide clear ways of linking and describing SES variables and interactions, allow for the application of multidisciplinary methods to articulate how social-ecological variables and interactions cause resource problems and deal with the dynamic aspects of SESs through time and space.

The social-ecological system diagnostic framework (SESDF) set out by Ostrom (2007, 2009) was selected as it met all but one of the above criteria. The SESDF has been widely applied to assess a variety of SES problems (Ostrom, Janssen and Anderies, 2007). Secondly, it builds on the strengths of previous analytical frameworks—most importantly the Institutional Analysis and

Development (IAD) framework, which exclusively focused on human activities that impact resource problems—as its design and function has been expanded to include ecological and environmental attributes and their linkages with human factors that can cause natural resource problems. Thirdly, its design includes all the variables that typically comprise SESs. As per *Figure 2*, highly relevant to the research aims of this dissertation, the variables included in the framework are: *Resource Systems* (aquifers contained in the watersheds that comprise the GLB), *Resource Units* (quantity of GWS), *Governance Systems* (binational, multilevel governance frameworks), *Actors* (institutions and non-governmental stakeholders). The SESDF also allows for evaluation of their *Interactions* (cooperation and coordination between actors and GWS–governance feedbacks) and *Outcomes* (long-term GWS levels in high-stress locales).

Figure 2: Basic Structure of the SES Framework (*Source: Ostrom, Janssen and Anderies, 2007*)



Fourthly, the SESDF provides a clear way to link the interactions of these variables that have outcomes on natural resource sustainability. Variables and linkages can be hierarchically arranged in levels (i.e., first, second, third, fourth, etc.) enabling analysis to zoom in and out of multilevel governments (from binational to municipal) and multi-scale groundwater flow systems (from Basin-wide to sub-watershed) to identify cross-scale and cross-level linkages between human and environmental variables that impact long-term GWS availability in high-stress locales.

By explicitly allowing for the consideration of cross-linkages between different classes of variables, the SESDF can facilitate the use of a range of methods, perspectives, evaluative criteria and theories to assess cause and effects, thereby meeting the final selection criterion of allowing multidisciplinary approaches to explain real world observations.

The weaknesses of the SESDF identified in the literature (Ostrom, Janssen and Anderies, 2007; Ostrom, 2009) are not expected to have major negative impacts on the research. One weakness pinpointed is that the SESDF is biased towards the analysis of CPRs. Since groundwater is a CPR, this bias is advantageous for this body of research. Another shortcoming is that it does not allow for the codification of factors that cause problems in a wide array of CPRs as it is not suited to large numbers of units of analysis. Relatedly, it is not suitable for establishing causal relationships which require statistical methods. Rather, the SESDF is ideal for drawing in-depth insights about causal relationships through case-study research. As the causal relationship between governance and GWS will be demonstrated in this dissertation through statistical analysis in a case study of the City of Guelph, this is not a limitation but an advantage. Despite its relative biophysical sophistication compared to the IAD, another identified weakness is that the SESDF encourages analysis of human-environment interactions and outcomes from an anthropocentric perspective.

The research perspective of this dissertation is strongly anthropocentric as it is based on human observations of changes in groundwater storage that result from governance (application of human use rules, decisions and processes) that may or may not be well suited to groundwater resource sustainability in high-stress locales. The SESDF fails to meet one selection criterion, which is the functionality to deal with the dynamic aspects of SESs through time and space. However, this is mitigated by the dissertation’s assessment of the long-term impacts of governance on GWS from an ex-post analytical perspective (further elaborated in *1.5.2* below), using historical groundwater quantities resulting from water use governance in the City of Guelph case study to evaluate governance–GWS impacts.

1.5.2. Analytical perspectives

Analytical perspective refers to the point of view of considering relevant data and variables to establish their meaningful relationship (Bardach, 2012). To assess the degree to which the GWS governance framework addresses groundwater quantity sustainability concerns in high-stress situations of the Basin, perspective(s) that facilitate the identification and evaluation of causal relationships and pathways between multilevel governance and GWS is required. Additionally, to use these findings as a basis for the proposal of principles for a reformed GWS governance framework applicable to high-stress sub-watersheds of the Basin also requires perspective(s) that can draw relevant lessons that can be realistically applied to these situations. Described and justified below, the analytical perspectives applied in this dissertation vary given the differing specific research objectives (see *1.5.1*) and multidisciplinary methods (see *1.5.3*) required.

- *Ex-Post Analytical Perspective*

The predominant perspective used in this dissertation is the ex-post analytical perspective as it facilitates the analysis of data and knowledge of past to present changes in phenomena that can be useful in discerning the intended and unintended effects of governance initiatives on natural resources over time (Bardach, 2012). Based on the characteristics of overdeveloped aquifers as defined by UNESCO (Foster and Loucks, 2006), if governance is having an unsustainable outcome on groundwater resources, this can be discerned using the ex-post analytical perspective by examining historical or long-term, persistent declines in the GWS indicator(s) being observed. In so doing, this approach can aid assessments of whether specific governance interventions (described in the review of multilevel GWS governance in *Research Objective I*) have been working as expected in high-stress situations (described in the review of GWS levels in vulnerable sub-watersheds in *Research Objectives II* and *III*) and allows for the use of multidisciplinary methods to identify likely reasons why interventions have or have not been working.

As the ex-post analytical perspective allows for a look back at the groundwater quantity impacts of the past to appraise the performance of the GWS governance framework, its use is justified by the inability of the SESDF to facilitate discussion of the spatio-temporal dynamics of human-ecological processes over time (Ostrom, Janssen and Anderies, 2007; Ostrom, 2009). Additionally, this perspective allows for the articulation of a starting point or "baseline" of governance and GWS conditions from which to trace the major governance changes that have occurred since the first binational treaty applicable to governing GWS levels (needed in *Research Objective I*). Tracing goes from the *1909 Boundary Water Treaty*, to the first good faith agreement governing GWS use—the *1985 Great Lakes Charter*, to the present-day legislation of the *2005 Great Lakes - St. Lawrence Basin Sustainable Water Resources Agreement* in the GLB states/province. This perspective is also justified in *Research Objective III* in demonstrating the utility of subsidiarity in improving adaptive governance as needed to enhance the sustainability of GWS in high-stress locales, as this will be done using historical GWS data to ascertain the impacts of governance.

- *Case Study Perspective*

Case study perspectives also feature heavily in this dissertation. To validate hypotheses, researchers typically use large-*N*, randomized approaches to provide the degrees of freedom and broad situational applicability needed to validate theory (Bardach, 2012). However, substantial time and resources are typically required to consider a large number of representative units of analysis. Researchers with more resource constraints and/or different research objectives often use case-study based approaches as they involve in-depth analysis to determine causes of phenomena in specific situations. Although this analytical perspective is inherently limited in its ability to build theory, for the purposes of this dissertation it is sufficient given the focus on appraising governance GWS impacts in high-stress locales, which represents a specific situation in the GLB that is otherwise water abundant.

The case study perspective is used in *Research Objective III* to demonstrate the utility of mainstreaming subsidiarity with a study of groundwater quantity governance outcomes in the City of Guelph, Ontario. In *Research Objective IV*, the findings of this case study prove useful in developing proposals to reform the GWS governance framework to better sustain groundwater quantities in high-stress sub-watersheds based on an actual GLB situation. For future research, as this case is representative of sustainable GWS outcomes in high-groundwater-stress locales that include WMOs and municipal institutions in multilevel governance, the findings may be useful in large-*N* meta-analyses aimed at building theories supportive of adaptive governance and mainstreaming subsidiarity to improve GWS governance in the GLB.

- *Broadly Comparative Case Study Perspective*

A broadly comparative case study perspective is also used in *Research Objective II* to develop a baseline of governance outcomes on GWS in high-stress situations throughout the Basin. In the absence of opportunities for large-*N* analysis, this analytical perspective allows for the consideration of a relatively small number of comparable cases and a limited number of variables to test hypotheses (Poteete, Janssen and Ostrom, 2010). In linear algebra, this perspective can be expressed as:

$$Y = b\,x1 + bx2 + bx3 + ei$$

Where:

Y is the dependent variable*;*

b is the independent variable;

x1 is the ith value of the independent variable; and

ei is the margin of error/variability of the dependent variable not attributable to the independent variable(s).

Applied to research, this analytical perspective facilitates investigation focused on providing a broad overview of the present situation of GWS decline (***Y***) that is occurring in high-stress locales of the Basin as a result of multilevel groundwater quantity governance. It allows for the selection of cases that are sufficiently representative of the (***b***) different combinations of the human and environmental factors that influence decline in GWS in high-stress situations and the varying multilevel governance arrangements applied in these situations throughout the Basin. By conducting a standardized review of officially reported GWS decline cases in all GLB states/province (methodology elaborated in *1.5.3.*), cases reviewed are representative of the jurisdictionally varying governance initiatives used to manage high-stress GLB locales (***bx1***) and diversity in physical-environmental settings and/or stressors (***bx2***) and human and/or natural groundwater users that impact GWS (***bx3***). The margin of error (***ei***) is dealt with in the probabilistic analysis to statistically determine the causal relationship between governance and GWS in *Research Objective III.*

In the context of the research aims and in consideration of time and resource constraints, the use of the broadly comparative case study perspective is justified as it can identify governance outcomes on GWS sustainability while evaluating the generality of these relationships within a broader population of cases. The application of this perspective adequately supports the research objectives while still providing some empirical evidence needed for validity and hypothesis testing given the full extent of the human-ecological diversity of the local physical-environmental settings that control GWS; the GLB spans many climate zones and is disaggregated into more than 186 aquifers that may be bedrock-hosted, fractured, sedimentary rock-hosted, confined or unconfined (Granneman *et al.*, 2000). The anthropogenic activities and ecosystems that depend on groundwater are also diverse, including but not limited to stream baseflow and intense human users in the agricultural industry or municipal water supply.

1.5.3. Analytical theories

Analytical theory can be defined as an established explanation of phenomena in the natural world based on a well-substantiated body of facts that have been frequently confirmed via experimentation and observation (Bardach, 2012). The interpretation of the cause-effect linkages between governance and groundwater needed to evaluate the suitability of a governance framework to maintaining GWS in high-stress locales requires considering a diverse array of human and environmental variables within the GLB SES that may potentially contribute to resource depletion. Nagendra and Ostrom (2014) note that "many of these variables may be important or necessary, but not sufficient, and thus difficult to attribute causality to them." To identify the important variables, ascertain their roles and assess their linkages, it is necessary to apply relevant theories to the SES diagnostic framework (discussed in *1.5.1*) to identify the most important variables and evaluate their roles in resource depletion and/or maintenance (Ostrom and Cox, 2010). Collective action and CPR sustainability theories are particularly useful in this regard as they provide assumptions that are required to evaluate the linkages between governance and groundwater sustainability problems.

CPR sustainability theory applied to groundwater rests on the concept of sustainable yield: the quantity of the stock of a natural resource that can be used without reducing the quantity needed to maintain its environmental flows and/or ecosystem services (Walton and McLane, 2013; Maimone, 2004; Bredehoeft, 1997). Aquifers store a finite set of groundwater stocks that are innately limited by their storage capacity: the maximum water volume that can be stored in the interstices and voids of an aquifer's geological material (Maimone, 2004). GWS stocks result from a defined rate of inflow typically from natural precipitation and outflow from natural discharge to surface water bodies and increasingly from human pumping. GWS is susceptible to long-term changes in precipitation patterns that are increasingly induced by climate change and the policies and decisions made by governments that control land zoning (that impacts natural recharge), groundwater use and pumping, as multilevel governments set the conditions for groundwater withdrawal and conservation within their jurisdictions (Walton and McLane, 2013). As all of an aquifer's recharge is typically discharged to surface water bodies, when governments allow groundwater to be pumped at a rate that exceeds the small fraction of recharge that can be taken without negatively impacting GWS, surface waters and other environmental flows and services, an aquifer is considered to be unsustainably developed (Van Camp, Radfar and Walraevens, 2010).

The sustainable aquifer yield premise is essential for evaluating the suitability of the governance framework to maintain GWS in high-stress situations as it involves policy- and decision-making that balance the opposing strategies of little to no pumping to conserve GWS, streamflow and other ecosystem services, or the total appropriation of natural discharge for human uses, with the overall aim of avoiding negative environmental, social, cultural and legal outcomes

(Walton and McLane, 2013). Simply put, if governance leads to outcomes that sustain sufficient GWS stocks for long-term human and environmental uses in high-stress sub-watersheds, it can be assessed as suitable for the specific socio-environmental needs and conditions in that particular locale. Researchers can then identify and evaluate particular policies, practices and decisions based on the hydrogeological and groundwater sustainability sciences that relate to the physical-environmental needs to maintain sustainable yield in that particular setting (Grey and Sadoff, 2007). If long-term declines in GWS and negative impacts on related environmental systems are the general outcome of governance, it can be assessed as insufficient. As such, gaps and features can be identified that may contribute to unsustainable use and insufficient conservation given the locale's particular socio-environmental settings.

The retrospective analytical approach is also important as it allows for the assessment of long-held characteristics of past GWS governance that can be useful to deepening understanding of present-day policy features that underlie GWS vulnerabilities (Nelson and Quevauviller, 2016). It can also help to confirm inferences of why policies have led to current outcomes, directly useful for decision-making on future policy directions (Dunn, 2011). Three types of questions typically guide retrospective policy analysis: (i) What happened to the policy problem earlier? (ii) Were policy objectives met? and (iii) What should be done for the future courses of action? (Dunn, 2011). These questions enable greater appreciation of the logic, deliberations and scientific understanding behind the legal principles underpinning present-day GWS governance in the Great Lakes region. They also allow increased understanding of the governance processes and mechanisms (amendments, long-standing jurisprudence, etc.) by which policies clearly unsuitable to GWS sustainability are able to persist over the years. With this understanding, high-impact recommendations for GWS governance reforms, covering both governance mechanisms and scopes of policies and decision-making standards, may be proffered.

In evaluating the GWS governance framework and developing proposals to improve groundwater quantity governance in high-stress sub-watersheds of the Basin, theories related to collective action are also important. Collective action theory first emerged as a response to transfers of property rights and community ownership of CPRs to governments in the 1960s and 1970s as a result of “New Deal” governance style (Ostrom, 1990). These developments were underpinned by the seminal work of Garret Hardin in *Tragedy of the Commons* (1968), which posits that in a world with finite resources, without hegemonic governmental or private enterprise control of common resources, “Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a common brings ruin to all.”

Researchers observed that this centralized, top-down approach to governance often produced negative unintended consequences including the rejection of indigenous rights (Kronk and Ann, 2015) and poor monitoring of natural resource use, which gave rise to “de facto” open access conditions and the degradation of many CPRs. Important critiques of the conceptual underpinnings and applications of Hardin’s theory include Ostrom’s (1990) *Governing the Commons*, which argues that individuals have the capacity to self-organize to rid themselves of unsustainable situations once they recognize the need to preserve the CPR for the common good. Another key challenge to the theoretical appropriateness of Hardin’s work came from the field of resource economics in the 1970s and 1980s from noteworthy academics such as Thompson (1975) and Ciriacy-Wantrup (1975). They argued that Hardin hadn’t differentiated concepts related to common property from open access conditions and that common property communities had instituted complex governance systems that controlled access rights to users with long-term interest in the resource, which served as a deterrent to over-exploitation.

On this basis, collective action was proffered as a viable alternative to sustainably manage CPRs, facilitating policy and institutional changes in governments to safeguard equitable and sustainable collective benefits. Based on numerous case studies, including groundwater conservation through collective action in Central Basin and West Basin California, Ostrom (1990) developed eight design principles for organizing collective action to sustainably govern CPRs. They are participatory, self-organized and self-imposed and include:

a. Clearly defined jurisdictional and CPR boundaries.
b. Rules governing use of common goods are matched to local needs and conditions.
c. Stakeholders affected by the rules can participate in modifying the rules.
d. Rule-making rights of community members are respected by outside authorities.
e. A system carried out by communities for monitoring members’ behavior is established.
f. Graduated sanctions for rule violators are in place.
g. Accessible, low-cost means for dispute resolution are provided.
h. Responsibility for governing the CPR is nested (according to governance themes) and tiered from the lowest to highest governance level.

Cox *et al.* (2010) confirmed the validity of these principles through the conduct of 91 studies where they were applied to evaluate the sustainability of collective action CPR governance.

Collective action-inspired approaches to environmental governance have become widely adopted over the last two decades (Marshall, 2007), with the processes of nesting, subsidiarity and adaptive governance increasingly employed to represent local, community interests in multilevel governance. In these processes, the “up-scaling” of community-based approaches is accomplished by nesting or aggregating smaller groups based on thematic similarities (i.e., interests in the management of a particular resource), providing the opportunity for increased governance flexibility and agility on the part of multilevel actors and institutions that promotes polycentric, adaptive governance. Collective action theories thereby empower local actors and reduce the likelihood that free loaders will be allowed to unsustainably use or impact the management of the resource. This is based on the notion that it is feasible to anticipate that local actors will play an increasingly active role and provide feedback on GWS policies and decision-making if their interests are increasingly negatively impacted by falling groundwater levels. As such, the extent to which the government is capable of sustainably governing GWS in vulnerable sub-watersheds can be evaluated in this dissertation, in part based on the extent to which collective action approaches are mainstreamed in multilevel governance. These concepts also influence the process of developing proposals for GWS governance reform.

1.5.4. General evaluative criteria

While there is no blueprint for sustainable GWS governance, given the need for it to be adaptable and flexible to location-specific sustainable yield and related socio-environmental conditions, it is possible to assess whether approaches are sustainable or not using universal evaluative criteria for sustainable governance (Lockwood *et al.*, 2010). Adapted to the overall objective of this dissertation and based on the principles of adaptive governance and subsidiarity, the evaluative criteria and research questions that provide general guidance throughout this body of research are outlined in *Table 3* below.

Table 3: General Evaluation Guidelines for Sustainable Governance (Source: *Lockwood et al., 2010*)

Evaluative Criteria	**Evaluative Questions**
Adaptability	- Do multilevel governments proactively identify potential risks and opportunities for effective GWS governance at the sub-watershed scale? - Are iterative approaches used for science-based governance including mechanisms to incorporate location-specific and/or new findings and data into decisions and policies?
Integration	- Is subsidiarity mainstreamed? ✓ Is there coordination and alignment between and across different government levels? ✓ Is the authority to carry out GWS governance roles and responsibilities equally distributed amongst multilevel governments? ✓ Are there mechanisms in place for data and information sharing across and within binational federal governments? ✓ Are there mechanisms in place to engage with non-governmental stakeholders in GWS governance?
Inclusiveness	✓ Are there opportunities for multilevel government and non-governmental stakeholders, including the general public, to participate in GWS policy development and decision-making?
Fairness	- Do power dynamic asymmetries exist? ✓ Are decision-making and policy development in binational to multilevel governance free from special interests and inherent bias? ✓ Are benefits associated with decisions and policies directly impacting GWS adequately considered and distributed by the relevant institutions and actors to stakeholders?
Capability	- Do multilevel government institutions and actors have the human and financial capacities to deliver on their GWS governance mandates?
Legitimacy	- Have laws and the general citizenry provided authority for multilevel actors and institutions to govern?
Transparency	- Is there a clear logic for decisions? - Are decision-making processes and structures visible to all government and non-governmental stakeholders, including the general public?

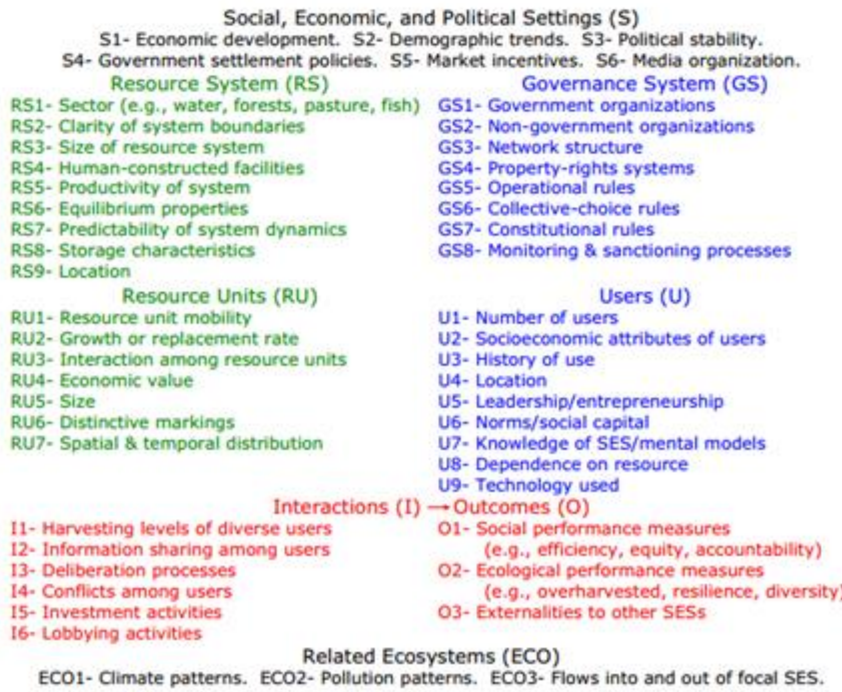
1.5.5. Analytical methods

Given the scope of the research in this dissertation, the applied multidisciplinary methods predominately draw from the hydrogeological, engineering and political sciences. The logic, evaluative criteria and methods applied in each of the core research chapters are organized in *Table 4* below.

Table 4: Analytical Methods Framework

Chapter 2: Identifying Groundwater Sustainability Implications of Water Policy in High-Use Situations in the Laurentian Great Lakes Basin		
Logic	- To identify the governance framework features that have the strongest linkages with or impacts on groundwater storage in vulnerable sub-watersheds of the GLB. - To glean greater insights into the overall governance approaches used across jurisdictions of the Basin useful to selecting the ideal case study to represent a jurisdiction where municipal governments and WMOs are involved in multilevel GWS governance in *Chapter 3.*	
Analytical Approach	SESDF	Application of the typical attributes of the Governance System Variable of the SESDF (Ostrom, Janssen and Anderies, 2007) to identify relevant governance features.
	Variables	Governance System (GS) GS1- Government organizations GS2- Non-government organizations GS3- Network structure GS4- Property-rights systems GS5- Operational rules GS6- Collective-choice rules GS7- Constitutional rules GS8- Monitoring & sanctioning processes
	Perspective	Broadly Comparative Research
	Theory	Collective Action; Sustainable Aquifer Yield
	Evaluation Criteria	Adaptability, Transparency, Fairness, Inclusiveness, Integration, Capability, Legitimacy
Research Method	The identification of governance features and gaps that can lead to GWS depletion in drought-prone or high-use locales of the Basin was systematically based on the typical attributes of the Governance System in the SESDF (Ostrom, Janssen and Anderies, 2007). Data and information were sourced from an extensive review of official government legislation, regulations, reports and publications accessed via designated government portals and websites. Theories related to sustainable aquifer yield and collective action (specifically Ostrom's eight design principles for sustainable CPRs) were applied to evaluate features of the governance framework. Evaluative criteria were distilled into three main modes of appraisal: the extent to which the governance framework (i) defined the feasible aquifer pumping rate and groundwater conservation rules appropriate to the available quantity of groundwater in aquifers and geological environmental controls; (ii) monitored groundwater levels to assess the impacts of use on GWS; and (ii) implemented rigorous surveillance programs to monitor and disincentivize lapses in adherence to	

	groundwater use regulations based on democratically agreed-upon processes. The development of recommendations to bridge identified governance gaps was based on principles of subsidiarity and sustainable CPR principles developed by Ostrom (1990), using brief case studies to demonstrate the potential benefits of adaptive governance in maintaining GWS in high-stress situations.	
Chapter 3: Twenty-first Century Science Calls for Twenty First Century Groundwater Use Law: A Retrospective Analysis of Transboundary Governance Weaknesses and Future Implications in the Laurentian Great Lakes Basin		
Logic	- To assess the extent to which the governance framework has achieved groundwater security in the past in a drought-prone and groundwater-dependent locale of the GLB. - To trace the evolution of contemporary GWS governance to identify the origins of governance weaknesses and uncover the governance processes that have enabled them to persist over time, despite evidence of their unsuitability in high-stress locales.	
Analytical Approach	SESDF Variables	Application of the typical attributes of the Governance System Variable of the SESDF (Ostrom, Janssen and Anderies, 2007) to identify relevant governance features. Governance System (GS) GS1- Government organizations GS2- Non-government organizations GS3- Network structure GS4- Property-rights systems GS5- Operational rules GS6- Collective-choice rules GS7- Constitutional rules GS8- Monitoring & sanctioning processes
	Perspective	Broadly Comparative Research; Retrospective Analytical
	Theory	Collective Action; Sustainable Aquifer Yield
	Evaluation Criteria	Adaptability, Transparency, Fairness, Inclusiveness, Integration, Capability, Legitimacy
Research Method	The methods used in this chapter correspond to two distinct sections of the paper. The first involves the documentation of cases of emerging GWS vulnerabilities throughout the Basin using the broadly comparative case study approach. Herein, based on desk studies of publicly available reports from multilevel groundwater governance institutions, cases were identified based on a comprehensive set of GWS decline indicators typically used in industry. The second involves retrospective analysis, applying the Causal Process Tracing method. This approach relies on carefully documenting milestones of GWS governance over time and interpreting them through the theory and hypothesis of how (Causes) origins of GWS governance in 19th-century common law can be linked to (Outcomes) current governance weaknesses and GWS insecurity outcomes.	
Chapter 4: What Can We Learn About Improving Multilevel Groundwater Quantity Governance in the Laurentian Great Lakes Basin from the City of Guelph, Canada?		
Logic	- To explain why governance features are or are not working in a situation where subsidiarity is relatively well-mainstreamed as compared to other locales in the GLB facing vulnerabilities in GWS.	
Analytical Approach	SESDF	The case study applies all the attributes of the variables component to an SESDF (Ostrom, Janssen and Anderies, 2007) to ascertain the interactions

	Variables	and reasons that led to sustainable GWS outcomes in the City of Guelph, Ontario, as well as areas for further improvement. 
	Perspective	Broadly Comparative Research; Ex-Post Analytical; Case Study
	Theory	Collective Action; Sustainable Aquifer Yield
	Evaluation Criteria	Adaptability, Transparency, Fairness, Inclusiveness, Integration, Capability, Legitimacy
Research Method	The methods used in this chapter correspond to two distinct sections of the paper. The first section involved the case study of the City of Guelph wherein the degree to which GWS was determined by groundwater governance compared to natural interactions via precipitation was evaluated using correlative analysis using Pearson's correlation co-efficient. Historical pumping rates provided by the municipality were used as a proxy for governance, and precipitation and GWS levels for the corresponding period were gleaned from publicly available records. In the second section of analysis, evaluative criteria based on collective action and sustainable aquifer yield theories were used to identify and evaluate the governance features that were likely the reasons for the maintenance of GWS in the City despite its location in both a drought-prone and groundwater-reliant region.	

1.6. Thesis Organization and Overview of Chapter Contents

The remainder of this dissertation is organized accordingly:

Chapter 2 examines policies, from the binational to municipal government levels, to identify gaps and features that can lead to GWS decline in aquifers supplying high-use hotspots in the Basin. The criteria used to identify and assess these policy gaps and features are adapted from global sustainable groundwater quantity management standards set by the United Nations (Morris *et al.*, 2003). These criteria include: (i) definition of the feasible aquifer pumping rate appropriate to the available quantity of groundwater in aquifers and geological environmental GWS controls, (ii) monitoring of groundwater levels to assess the impacts of use on GWS, and (iii) implementation of a rigorous surveillance program to monitor adherence to groundwater use regulations.

The study is based on an evaluation of governance practices and policies in the form of laws, rules, reports and publications from official government sources. Data was also sourced from responses to a survey distributed to each of the state- and provincial-level institutions governing GLB water resource use. Survey questions were designed to provide insight into the degree to which these institutions (i) set regulations specifically for groundwater use and for granting permits to take large volumes of groundwater; (ii) had established tools and processes to enforce compliance with regulations and the terms of permits to take large volumes of groundwater; (iii) monitored groundwater levels; (iv) were observing cases of persistent GWS decline in aquifers within their jurisdictions; and (v) engaged with municipal-level institutions in groundwater use governance.

As the physical-environmental characteristics that determine the optimal rate at which groundwater may be abstracted from aquifers span many climates and geological settings within the Basin, the research findings point to the need to adapt groundwater governance policies and practices to local conditions. On this basis, recommendations are made for devolving more management roles to municipal-level institutions which, as the nexus between communities and central governments, may be better positioned to set policies that consider the competing interests of groundwater users within their jurisdictions as well as the unique physical-environmental characteristics of sub-watershed scale aquifers.

Considering the governance gaps highlighted in *Chapter 2, Chapter 3* is a retrospective analysis of the century-long evolution of the contemporary groundwater quantity governance framework. Using the same sustainable aquifer yield evaluative indicators, it aims to uncover persistent policy gaps and deduce governance processes through which policy pathologies have persisted over time to lead to present-day GWS governance weaknesses and contribute to growing groundwater insecurity across the Basin. It applies the Causal Process Tracing (CPT) method, a retrospective analytical approach that is ideal for deducing change and causation within temporal sequences of events. The chapter characterizes the outcomes of historical GWS governance: (i) first highlighting the prevalence of sub-watershed scale GWS vulnerabilities by collating reported cases of sub-watershed scale GWS decline throughout communities in the GLB states and Ontario, using the full range of possible indicators to estimate long-term GWS trends; (ii) and then recapping present-day GWS governance gaps. Data for this was sourced from a desk study of official government and peer-reviewed publications as well as responses to a survey distributed to state/provincial and municipal institutions.

Significant milestones and/or changes in policies and decision-making standards over the timeframe of the evolution of the GWS governance framework were then systematically identified using the CPT approach, applying sustainable aquifer yield criteria as evaluative indicators. In so doing, successive binational treaties, statute amendments, major court decisions and other governance mechanisms influencing GWS from its origins in 19th-century common law to the signing of the *2005 GLSWRA* and *2020 United States–Mexico–Canada Free Trade Agreement* (*2020 USMCA*) were assessed.

The findings highlight the surprising prominence of policies intended to safeguard surface water quantities employed to govern groundwater use and thereby maintain GWS over the years. Moreover, historical tracing determined that current policies and decision-making standards are based on court rulings that considered 19th-century groundwater science and have not kept pace with scientific innovations that are much better positioned to quantify and determine underground flow directions of groundwater flow systems. The paper urges fundamental reforms, matching 21st-century groundwater science, to develop policies and decision-making standards considering the physical-environmental limits of groundwater, which are distinct from those of surface water resources, to better maintain the resource in drought-prone and/or groundwater-dependent communities.

Chapter 4 is a case study of groundwater quantity governance in the City of Guelph aimed at demonstrating the potential GWS sustainability outcomes of sufficient mainstreaming of subsidiarity whereby significant GWS governance responsibilities are devolved to GLB municipal institutions. The City of Guelph was chosen for the case study as it is located in a drought-prone region of the GLB and is wholly groundwater-dependent, with groundwater demand projected to grow given that it is amongst the fastest-growing urban centers in Canada. However, it is distinguished from other municipalities facing similar climate and population pressures as it was found to have maintained GWS quantity in its developed aquifers. The case study identifies the features of the multilevel governance framework applied in the City that led to long-term GWS stability, with a view to drawing lessons instructive for the development of more sustainable groundwater quantity governance in vulnerable locales of the GLB.

The case study commenced with a linear correlation analysis to ascertain the degree to which policy (indicated with historical pumping rates) impacts GWS (indicated with historical groundwater levels of aquifers within the City of Guelph) as opposed to precipitation. Historical precipitation data from 2002 to 2017 was sourced from an official government database; the City of Guelph provided corresponding groundwater table levels and pumping rate data. Correlation analysis showed that policy is a stronger determinant of GWS than precipitation, suggesting that the City has been able to maintain stable GWS for the study period due to features of its GWS governance framework.

The main governance features that were deduced to have supported GWS sustainability include: (i) the City's water use bylaws, which increased restrictions with drought intensity and were enforced with rigorous monitoring and fines for non-compliance; (ii) the science-based policy prescriptions of the Grand River Conservation Authority that informed the City's graduated water use bylaws and other water conservation measures—the Conservation Authority being one in Ontario's system of hydrological research institutions with jurisdictions defined by watershed boundaries that is staffed by municipal and technical personnel; (iii) a legal mandate to include Ontario's municipalities in the provincial government's decision-making to grant permits to take large volumes of water; and (iv) lower volumetric water use rate triggers requiring a permit in Ontario than the other GLB states (except for Minnesota).

These findings suggest that the lack of municipality involvement in governance is under-utilizing their potential to address GWS vulnerabilities. Inherent municipality characteristics that are conducive to effectively addressing location-specific GWS vulnerabilities include: (i) better matching of governance and aquifer scales; (ii) greater institutional flexibility to address local needs and adapt to changing environmental conditions than higher levels of government; and (iii) better use of municipal institutions and laws to monitor and enforce groundwater conservation policies given the closer proximity to groundwater users.

Chapter 5 constitutes the conclusion of the dissertation with a discussion of its contributions, limitations and potential future research directions on this topic. It also provides a framework of good governance principles to lead to sustainable GWS outcomes in vulnerable locales throughout the Basin. The proposed framework promotes greater democratization of decision-making impacting GWS by devolving greater governance responsibilities to municipalities, better science–policy alignment by urging the separation of groundwater use and conservation laws from GLB surface water laws and ensuring that such laws keep pace with innovations in groundwater science, and greater harmonization between economic and groundwater use policies and decision-making standards.

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2. CHAPTER 2

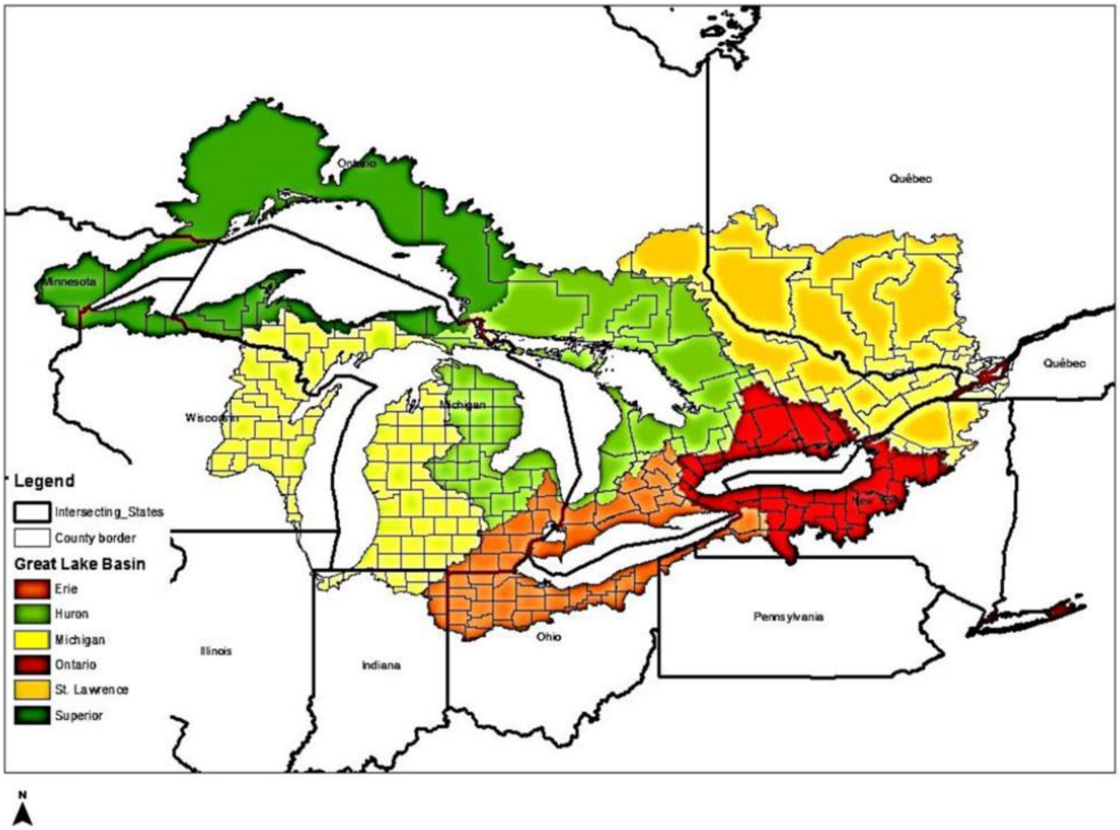
Weekes, K., Krantzberg, G. and Vizeu, M. 2019. "Identifying Groundwater Sustainability Implications of Water Policy in High-Use Situations in the Laurentian Great Lakes Basin.". *Canadian Water Resources Journal*, 44 (4): 337-349. DOI:10.1080/07011784.2019.1623079

ABSTRACT

Although the Laurentian Great Lakes Basin contains the largest global store of fresh water, long-term groundwater storage (GWS) decline has been observed in some aquifers supplying communities that intensely use the resource. We consider a hallmark of effective groundwater use policy to be the regulation of aquifer pumping rates consistent with the physical-environmental determinants of sustainable aquifer yield. In this context, we examine policies, from the binational to municipal governance levels, to identify features that can lead to GWS decline in aquifers supplying these communities. As the physical-environmental characteristics determining sustainable yield span many climates and geological settings within the Basin, our findings highlight the need for policies to adapt to local conditions. We urge devolving more management roles to municipal level institutions which, as the nexus between people and central government, may be better poised to set policies in a participatory manner considering the unique physical-environmental characteristics of the aquifers on which their communities rely.

2.1. Introduction

Figure 3: Map of Government Jurisdictions and Main Sub-Basins of the GLB (*Source: authors' compilation*)



Spanning nearly 1 million km^2 over parts of the US states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, Wisconsin and the Canadian province of Ontario, the Laurentian Great Lakes Basin (GLB; *Figure 3*) is the world's largest freshwater reserve (Sterner *et al.*, 2017). Despite its water abundance, the GLB is characterized as having potential for groundwater shortages developing in communities that intensely use the resource (Reeves, 2011). As there has been relatively little research exploring the role of policy in sustaining GLB groundwater storage (Rivera, 2015), this paper's aim is to identify the policy features that can lead to overuse and groundwater storage decline in aquifers pumped by the Basin's high-use hotspots or "groundwater communities."

The GLB supplies the world's first and second highest per capita water users, as the average American and Canadian use 364 litres/day and 251litres/day, respectively (USGS, 2016a; ECCC, 2017). Although surface water is mainly used by the Basin's 42 million residents (2016 census of GLB municipalities), its 4,168km^3 of stored groundwater (Granneman *et al.*, 2000) is becoming increasingly important to support the US $6 trillion regional economy (Kavcic, 2016). Some 8 million, mainly rural, residents use groundwater as their sole drinking water source (GLSAB, 2010). Some 160 billion litres/day of water are pumped for public supply, agriculture, manufacturing, energy and commerce, of which the total consumption of groundwater - withdrawn groundwater not returned to source aquifers - is estimated at 16 billion litres/day (GLC, 2016). Compounding this, groundwater is exported from the Basin via emerging industries such as water bottling and pharmaceuticals (Schaffer, 2008; Wolfe, 2014).

More typical in arid or semi-arid regions of the world, increasing groundwater use raises sustainability concerns (Morris *et al.*, 2003). We define sustainability as enabling the level of resource use for current needs without reducing future generations' ability to meet their needs. Sustainable groundwater use policy is based on sustainable aquifer yield: a rational compromise between the opposing strategies of little to no pumping, or the total appropriation of natural discharge to avoid negative environmental, social, cultural and legal outcomes (Walton and McLane, 2013).

In the context of the physical-environmental requisites for sustainable aquifer yield, maintaining groundwater storage (GWS) is based on groundwater's classification as a common pool resource. Aquifers consist of a finite set of water units that are inherently limited by their storage capacity: the maximum water volume that can be stored in voids and interstices of its geological material (Maimone, 2004). GWS is a derivative of a defined rate of inflow from precipitation and/or artificial recharge, and outflow from natural discharge to surface waterbodies and/or pumping. Hence, GWS is vulnerable to climate change, land zoning and increasingly, human overuse. As all of an aquifer's recharge is usually discharged to surface water bodies, when groundwater is pumped at a rate that is higher than the small fraction of recharge that can be taken without consequence on surface waters, an aquifer can be overexploited. Furthered by consumptive use, persistent GWS decline can lead to groundwater shortages as competing demands increase over time (Van Camp, Radfar and Walraevens, 2010).

Based on survey responses from water management institutions in the GLB states and Ontario, long-term GWS decline appears to be occurring in some aquifers supplying communities in roughly 10 percent of the GLB's municipal jurisdictions. GWS decline has been correlated to communities that have intensely used pumped groundwater over many years (Feinstein, Hunt and Reeves, 2011). To highlight, the introduction of high-capacity pumps in the 1860s caused substantial GWS decline in the aquifers used by Milwaukee, Wisconsin and the metropolitan areas of Chicago, Illinois, including eight of its eastern suburban counties (Feinstein, Hunt and Reeves, 2011).

Major GWS declines have occurred in limestone aquifers supplying 16 of Michigan's municipalities, notably Kalamazoo County, Ottawa County, and the eight county metropolitan areas of Detroit (MDEQ, 2018). In Canada, GWS decline occurs in aquifers used by Waterloo Regional Municipality and the City of Guelph (MECP, 2017). As water vulnerabilities are attributed to inadequate management more so than environmental drivers (Aldaya, Martinez and Llamas, 2010), location specific GWS decline in the GLB may be indicative of a lack of fit between groundwater use policies and the physical-environmental requisites for the sustainable yield of aquifers.

Policies emanate from binational treaties between the US and Canada and the governments of the eight GLB states and Ontario, 263 municipalities and 120 Native American and First Nations within the Basin (Robinson *et al*., 2018). We analyse these multilevel policies from a technical point of view to shine light on where they can fall short in preventing overuse and GWS decline in the GLB's groundwater communities. Our analysis is limited to policy monitoring as we do not seek to establish a causal relationship between policy and GWS which would require quantitative methods (Schumann, 2016). We also omit policies from Quebec, as, although it collaborates in regional water management, it lies in the St. Lawrence River Basin (*Figure 3*).

The paper begins with an overview of the methods used to select and assess policies. We then undertake a critical review of international law on groundwater use in transboundary, international basins like the GLB to provide an analytical background. As these international guidelines can influence domestic groundwater use policies (McKay, 2007), this insight provides initial clues to describe how GLB policy can lead to GWS decline, given its mixed outcomes on GWS in many transboundary basins (Buis and Wilson, 2015). We then evaluate policies, from each GLB governance level, to identify the features that can fail to control overuse and lead to GWS decline. We conclude with a synthesis of findings and recommendations for future research.

2.2. Methodology

This study is based on the evaluation of policies in the form of legislations, regulations, reports and publications sourced from official government portals and websites. As our research pertains to the effects of overuse on GWS decline, the types of policies selected for evaluation were limited to those directly guiding the general conditions of GLB groundwater use, consumption, diversions and pumping rates. Policies indirectly impacting GWS were not assessed, including land zoning and climate change adaptation policies impacting recharge as well as water quality policies. Native American/First Nations policies were omitted as federal governments purportedly act on their behalf per fiduciary duties to execute treaties (Robinson *et al.*, 2018).

A standardized questionnaire was distributed to each of the nine state/provincial institutions designated to manage water resource use. Responses were utilized to verify our selection of policies and to gain greater insight as to whether these institutions (i) set specific guidelines for groundwater use and for granting permits to take large volumes of groundwater; (ii) had tools and processes in place to ensure compliance with regulations and terms of permits to take large volumes of groundwater; (ii) monitored groundwater levels; (iv) were observing instances of persistent GWS decline in aquifers within their jurisdictions; and (v) collaborated with municipal bodies in managing groundwater use and monitoring groundwater levels. Except for the Department of Environmental Conservation of New York state, each state/provincial institution designated to manage groundwater use provided a formal response to the questionnaire.

To evaluate policies, we assessed the degree to which state/provincial water management institutions met the technical, sustainable management criteria to result in sustainable yield defined by the United Nations Environment Programme (Morris *et al.*, 2003).These criteria include: (i) definition of the feasible aquifer pumping rate appropriate to the available quantity of groundwater in aquifers and geological environmental controls; (ii) monitoring of groundwater levels to assess impacts of use on GWS; and (iii)implementation of a rigorous surveillance program to monitor adherence to groundwater use regulations.

2.3. Review of International Law on Groundwater Use in International Basins

Contemporary policies governing access to groundwater stored in international basins have their origins in 19th-century English Common Law. The groundwater rule allowed unlimited and exclusive rights to groundwater from the portion of shared aquifers within property boundaries. This was because it was reasoned that it was difficult to set withdrawal limits for a resource whose flow paths were discrete, and whose boundaries shifted seasonally and with use intensity (Dellapenna, 2013). On the other hand, the riparian doctrine, or surface water rule, applied reasonable use principles to manage access to transboundary surface waters aimed at preventing overuse on upper watersheds to ensure equal access to the resource by lower riparians (McKay, 2007).

For the most part, the advancement of international principles governing access to transboundary basins has focused on safeguarding surface water resources through application of the riparian doctrine without setting specific guidelines for groundwater use or consideration of the unique physical–environmental sustainability needs of aquifers to maintain GWS. While the first treaty governing access to transboundary waters was the *1815 Final Act of the Congress of Vienna*, relating solely to surface water, the first to include transboundary groundwater was the *1966 Helsinki Convention* of the United Nations International Law Commission (UNILC). Even then, the *Helsinki Rules on the Uses of the Waters of International Rivers* applied the riparian doctrine in setting guidelines for the use of both surface and groundwater (*Art. 2*).

International water law was further progressed with the endorsement of Integrated Water Resources Management (IWRM) in the 1992 International Conference on Water and Environment in Ireland. The Conference initiated the consideration of hydrological science in water use policy, highlighting the connectedness of surface water and groundwater sub-systems of the hydrological cycle and the need to move from political divides towards watershed boundaries to sustainably manage water access via participatory approaches (Cullet and Stephan, 2018).

While the *1994 Draft Articles on International Watercourses* (*1994 UNILC Report 89*) was the first to propose adoption of IWRM principles, it continued to treat groundwater as subsidiary to surface water. Although it included a duty to cooperate with other riparian states (demonstrating the influence of IWRM), its guide for the equitable utilization of international waters was based on the riparian doctrine. These same guidelines were carried through to the*1999 Convention on the Protection and Use of Transboundary Watercourses and International Lakes* (*Article 3, 6*), as well as the UNILC's *2006 Berlin Rules* which summarized international law customarily applied to govern transboundary water use to date.

More recent treaties have introduced policies that specifically relate to the sustainable yield of aquifers in international basins, explicitly considering physical-environmental settings and societal use factors in setting obligations for sustainable use of the resource (Richey *et al.*, 2015). In 2008, UNILC adopted 19 articles of the *Draft Law of Transboundary Aquifers* (*2008 DLTA*) to guide the sustainable use of transboundary aquifers and hydrologically connected transboundary aquifer systems that are spread across different States. The *2008 DLTA*, for the first time, proposed establishing channels for the exchange of groundwater use data and models to guide sustainable use of international groundwaters. It recommended that the UNESCO International Hydrological Program provide technical support to signatory nations to develop groundwater science capacities to inform policy. The *2008 DLTA* has not yet been ratified due to concerns about sovereign rights to mineral resources embedded in an international basin's water bearing strata which are guaranteed under *UN Resolution 1803* (*XVII*). However, some states have opted to include its principles in transboundary agreements including the *2010 Guarani Aquifer Agreement between*

Argentina, Brazil, Paraguay and Uruguay (Villar, 2016) and the *2015 Jordan-Saudi Arabia Agreement for the Management and Utilization of Ground Waters* (Brown and Magraw, 2016).

Though initial steps have recently been made to align international water law with hydrogeological science, researchers have attributed the long-standing focus on surface waters for the relatively incipient development of guidelines for sustainable groundwater access in international basins (Rajmani, 2012).As climate change amplifies the impacts of growing global populations and their attendant demands for groundwater stored in international basins (Stephan, 2017; Gupta and Conti, 2017), shortcomings in international water law have contributed to roughly 30 percent of international basins experiencing groundwater distress (Villar, 2016).

Some notable gaps in the *2008 DLTA* include the lack of guidance for sustainable use of confined aquifers in international basins. There is also unclear guidance on the application of international or domestic law to resolve cases of conflicting groundwater withdrawal rules in political divides of international basins, which undermines IWRM. There is some contradiction as the *2008 DLTA* says "Each aquifer State has sovereignty over the portion of a transboundary aquifer or aquifer system located within its territory" (Art. 2), while also indicating "states shall exercise its sovereignty in accordance with international law and the present articles" (Art.4). Finally, except for the *2008 Convention on the Protection, Utilization, Recharge and Monitoring of the Franco-Swiss Genovese Aquifer*, treaties signed after the *2008 DLTA* provide no guidance on monitoring and sanctioning to enforce policies. Identified below, these and other attributes can be found in multilevel policies of the GLB possibly contributing to GWS decline in groundwater communities.

2.4. Identification of Multilevel Policies Guiding Groundwater Use in the GLB

2.4.1. Binational level

At the binational level, there are two treaties and one non-binding agreement relevant to groundwater use management in the GLB. However, these do not include policies that specifically consider hydraulic and hydrogeological considerations of sustainable yield. The first legally binding treaty is the *1909 Boundary Water Treaty* (*BWT*). Without defining a specific method, the Treaty endorses reasonable use principles to ensure the US and Canada have equal access to all water bodies along their international border. It confirms sovereign rights to set national water use laws for non-boundary waters within the GLB. It also establishes the International Joint Commission (IJC) to coordinate the treaty and conduct relevant research to make recommendations in support of sustainable water management. The IJC has no powers to compel parties to comply with treaty terms, except to issue orders to maintain levels and flows of transboundary waters.

The second treaty affecting GLB groundwater use is the *1994 North American Free Trade Agreement* (*NAFTA*). Although the *United States-Mexico-Canada Agreement* (*USMCA*) was recently negotiated to replace *NAFTA* when signatory nations each formally legislate the new Agreement, its water trading policies remain the same. Water embedded in products is defined as a tradeable good and there is no differentiation between groundwater and surface water in setting the terms of trade. Parties are obliged to trade without prohibitive tariffs, minimum export prices or any other impeding measure. The *USMCA* will further reduce these impeding measures by removing trade restrictions on some agricultural products, a significant consumer of groundwater, and lowering tariffs to encourage small and medium sized enterprises to participate in free trade activities. In the event of inconsistency between *NAFTA*/*USMCA* and other treaties, including water conservation accords, *NAFTA*/*USMCA* obligations take precedence. *NAFTA* is the only current treaty with legal recourse to enforce its policies as local courts or international arbitration bodies may resolve cases where businesses perceive impediments to free trade.

The *2005 Great Lakes-St. Lawrence Basin Sustainable Water Resources Agreement* (*2005 GLSWRA*) is the latest in a series of binational good faith agreements, beginning with the *1985 Great Lakes Charter*, to set principles for the sustainable management of the quantity of 'all waters' of the Basin. Unlike earlier agreements, this is the first to have been passed into law by the GLB states and Ontario. Citing IWRM principles, parties are obliged to adopt a watershed-based, participatory decision-making approach and conduct scientific research to monitor impacts of use on water availability. Parties shall meet every five years to discuss cumulative impacts of use on water availability which may be used to modify Basin-wide water use standards. To allow water use in excess of set standards, a regional review process and consensus from the Great Lakes Council of Premiers and Governors (the Great Lakes Council) is recommended. Parties may also opt to independently set stricter water use standards to conserve water. Exceptions to these standards are restricted to straddling communities, provided they demonstrate that (i) water diverted from the Basin will be for public water use; (ii) local water sources have been depleted and alternatives other than GLB waters exhaustively considered; and (iii) diverted water will be used efficiently and returned to source watersheds meeting water quality and invasive species standards.

Despite these strong points, the *2005 GLSWRA* applies identical standards to guide surface water and groundwater use. Regional review is required for requests for (i) bulk withdrawals, defined as those exceeding 379,000 litres (100,000 gallons)/day in a 90-day period; (ii) all requests for diversions or consumptive uses outside of the Basin and intra-Basin transfers; and (iii) within

Basin water consumption proposals exceeding 19 million litres (five million gallons)/day in a 90-day period. The Agreement also allows the diversion of packaged water from the Basin without the Council's consent when in containers measuring less than 20 litres (5.7 gallons). Although GLB states and provinces may set their own standards for reasonable use of smaller volumes of water, binational participation and adherence to sustainable use principles are done in good faith. This is because the Great Lakes Council has no authority to intervene at smaller volumes.

2.4.2. Federal level

Federal laws complicate watershed-based, participatory approaches to groundwater management recommended by the *2005 GLSWRA* as they determine the degree to which the GLB states and Ontario may adopt regional standards or participate in regional decision-making. As the *1867 Canadian Constitution* accords title of federal lands and its water resources to the Canadian Federal Government, its role is limited to ensuring that GLB water uses do not harm fisheries, navigation, international relations, and First Nations' water rights. Hence, Ontario has much autonomy in passing *2005 GLSWRA* policies in provincial law and collaborating with the Great Lakes Council.

In contrast, the US Federal Government has a much greater role in managing GLB groundwater uses than the Canadian Federal Government. Property rights in US territory are accorded to the US Congress by the *Commerce Clause* of the *1787 United States Constitution*. Accordingly, it prohibits states from entering into any agreement or compact with other states, including those pertaining to water use, without Congress' consent. A 1941 US Supreme Court ruling expanded Congress' remit to include management of the use of groundwater in order to preserve watercourse levels to enable commerce on navigable waterways. The *1986 Water*

Resources Development Act reaffirmed the prohibition of diversions of all US waters without congressional consent.

As such, consent of the US Congress was required before the GLB states could legislate policies of the *2005 GLSWRA*. To do so, Congress passed the *2008 Great Lakes-St. Lawrence River Basin Water Resources Compact* (or the *2008 Compact*) that recognizes the Great Lakes Council and affirms many core policies of the *2005 GLSWRA*. The *2008 Compact* keeps the bulk water use definitions of the *2005 GLSWRA* requiring, within five years of ratification, that GLB states develop a database of any person withdrawing or consuming water greater than 100,000 gallons/day in any 30-day period. Within three years, states are required to (i) establish water conservation and efficient-use programs; (ii) gather data on water use and impacts on storage; and (iii) report these to the Great Lakes Council.

However, the *2008 Compact* differs from the *2005 GLSWRA* in important ways. Instead of seeking regional review and consensus-based agreement from the Great Lakes Council, as recommended by the *2005 GLWSRA*, it is the policy of the *2008 Compact* that existing state-level institutions regulate and manage water use standards as much as possible. The *2008 Compact* legally compels GLB states to negotiate only with each other to implement its policies, thereby relegating participation and acceptance of the *Great Lakes Council's* decisions to be done in good faith (Kane, 2017). On this basis, within five years, the *2008 Compact* requires GLB states to give the Great Lakes Council opportunity to comment on high water uses that are in excess of standards set in the *2005 GLSWRA* for bulk water consumption and withdrawals, as well as standards for out-of-Basin and inter-Basin diversions. It also requires that states set a permit program managed by state-level institutions, to regulate and manage new or increased high volume water withdrawals and consumption in the US side of the Basin.

2.4.3. State/provincial level

At the state/provincial level, jurisdiction-specific policies are applied to manage the use of volumes of GLB water resources that fall below bulk water use definitions of the *2005 GLSWRA*. Laws generally entitle landowners to reasonable use of groundwater in properties for domestic purposes, except in droughts when correlative allocations based on property size are imposed (National Research Council, 2007).

Each of the GLB states adopted policies of the *2008 Compact* by passing *Great Lakes-St. Lawrence Basin Sustainable Resources Compact Acts*. In Ontario, policies of the *2005 GLSWRA* were adopted in a 2007 amendment to the *Ontario Water Resources Act*. In 2014, policies came into effect in the *Ontario Regulation 225/14.* Summarized in *Table 1*, GLB states and Ontario have all complied with the regional mandate to encourage water conservation and use efficiency, and have conducted relevant research and data collection on large volume water users which are collated in a regional data repository. Apart from Illinois, these jurisdictions also meet the out-of-basin and intra-basin water diversion standards. Illinois is exempt due to a US Supreme Court decision *Wisconsin vs. Illinois, 449 U.S. 48*, which established the Chicago Diversion. As highlighted by the approval of the Waukesha, Wisconsin Diversion by the Great Lakes Council on the 21st June 2016 (GLSLCI, 2018), so far, the GLB states and Ontario have followed the straddling community exception standard for out-of-Basin diversions. However, as summarized in *Table 5*, the degree to which they have adopted the high water withdrawal and consumption approval standards set in the *2008 Compact* and *2005 GLSWRA* varies significantly.

Table 5: Compliance of Ontario and GLB States with 2005 GLSWRA Policies

Jurisdiction	Meets straddling community exception standard	Meets out-of-Basin and intra-Basin diversion standard	Meets consumptive use standard	Bulk Water Taking Permit Program meets GLSWRA standards	Stricter groundwater-specific permitting standards	Verifies permit standards are met	Promotes efficient use and conservation of water	Submits standardized monitoring and data reports to Great Lakes Water Use Database
Illinois[1]	Yes	No	Yes	No	Yes[2]	No	Voluntary	Yes
Indiana[3]	Yes	Yes	No	No	Yes[4]	No	Mandatory for Industrial Users	Yes
Michigan[5]	Yes	Yes	No	No	Yes[6]	No	Voluntary	Yes
Minnesota[7]	Yes	Yes	Yes	Exceeds[8]	Yes	Yes[9]	Voluntary	Yes
New York[10]	Yes	Yes	No	Yes	No	No	Voluntary	Yes
Ohio[11]	Yes	Yes	No	No	Yes	No	Voluntary	Yes
Ontario[12]	Yes	Yes	Yes	Exceeds[13]	No	No	Mandatory in times of drought	Yes
Pennsylvania[14]	Yes	Yes	Yes	Yes	No	No[15]	Voluntary	Yes
Wisconsin[16]	Yes	Yes	Yes	Yes	No	No	Voluntary	Yes

1. Does not comply with many *2008 Compact* policies as Wisconsin vs. Illinois, 449 U.S. 48, established the Chicago Diversion, and in so doing, defined the state's allocation of Lake Michigan's water to 3,200 cubic feet/second based on a 40-year average.
2. Illinois only permits bulk groundwater use for domestic water supply (*1996 Rules and Regulations for the Allocation of Water from Lake Michigan)*
3. *Indiana Great Lakes Basin Water Management Rule 312 IAC 6.2 e*
4. Permit needed for groundwater takings exceeding 1 million gallons/day in Indiana.
5. *Part 327, Great Lakes Preservation*, of *Natural Resources and Environmental Protection Act*
6. 2003 *Aquifer Protection and Dispute Resolution Act* sets withdrawal thresholds based on a regional groundwater model that can classify aquifers as overexploited.
7. *Minnesota Statutes, section 103G.801*
8. The trigger requiring a permit is 10,000 gallons/day in any 30-day period in Minnesota.
9. Minnesota monitors user compliance with the terms of permits requiring permit holders to install flow meters to measure water use.
10. *Part 602* of the *Official Compilation of Codes, Rules and Regulations of State Of New York*
11. *Ohio Revised Code 1522.05*
12. *Ontario Regulation 225/14*
13. The trigger requiring a permit is 50,000 litres/day in any 30-day period in Ontario.

14. *Pennsylvania Title 32 PS 817.22 Forests, Waters and State Parks Statute.*
15. Pennsylvania may fine permit holders up to USD$5,000 for non-compliance with terms of permits
16. *Wisconsin Code 281.35*

Most relevant to our research, Ontario, Illinois, Indiana, Michigan and Ohio are the only jurisdictions to include policies specifically for the management of GLB groundwater use. Except for Illinois, where the only criterion for granting high volume GLB groundwater withdrawal permits is that it be used for domestic purposes (*1996 Level of Lake Michigan Act: Rules and Regulations for the Allocation of Water from Lake Michigan*), these jurisdictions consider physical-environmental factors for granting high volume GLB groundwater use permits.

However, the potential positive GWS sustainability impacts that these groundwater specific policies could have may be limited in Indiana, Michigan and Ohio. These states have a higher water-withdrawal-rate trigger requiring permits than the 100,0000 gallons/day in a 30-daythreshold of the *2008 Compact*. In Indiana, a permit is required from its Department of Natural Resources (Indiana DNR) for plans to take groundwater exceeding one million gallons/day (*Great Lakes Basin Water Management Rule 312 IAC 6.2*). These may be curtailed if the Indiana DNR finds that withdrawals exceed the recharge capacity of aquifers, reduce stream flow below the daily mean, or stress fisheries. In Ohio, permits are mandatory for withdrawals over two million gallons/day from GLB aquifers. The Director of the state's DNR may revoke permits that reduce stream flow (*Ohio Revised Code 1522.05*).

Michigan's special provisions for withdrawing large volumes of groundwater are in Part 327, *Great Lakes Preservation of its Natural Resources and Environmental Protection Act*. Water withdrawal requests exceeding 100,000 gallons/day over a 30-day period do not require a permit or regional review. Instead, they must be registered through the state's online Water Withdrawal

Assessment Tool (WWAT). Information required for WWAT registration include withdrawal location, pump capacities, intended pumping rates and schedules and aquifer types and depths. Permits are required to take over two million gallons/day from any source (groundwater or surface water). Based on large scale groundwater models, the *2003 Aquifer Protection and Dispute Resolution Act* sets withdrawal limits for the state's GLB aquifers, and empowers the Michigan Department of Environmental Quality to investigate whether high-capacity wells are overexploiting aquifers and to issue remedial orders.

2.4.4. Municipal level

There are 263 Municipal government jurisdictions within the GLB: 44 within Ontario and 219 within the US side of the Basin. Municipalities in GLB states generally have not set groundwater use policies and are usually not consulted on decisions related to permits to take high volumes of groundwater. Instead, their role in preserving GWS is indirect and usually limited to groundwater quality protection. As mandated by the federal *1972 Clean Water Act*, US municipalities have developed local bylaws that define setbacks and recharge areas, conduct groundwater protection needs assessments and participate in the development of regional groundwater plans.

Ontario's GLB municipalities, like their US counterparts, generally do not directly regulate groundwater use and are instead focused on groundwater quality management. The key difference is that the *2001 Ontario Municipal Act* mandates the provincial government to consult with municipalities in making decisions to grant permits to take high volumes of water. In exceptional circumstances where municipalities totally rely on groundwater, such as the City of Guelph, bylaws control water use in droughts.

2.5. Assessment of Multilevel Policies Guiding Groundwater Use in the GLB

Based on our evaluation of the degree to which multilevel GLB policies included the sustainable management considerations of sustainable yield, we found significant gaps in multilevel policies that can lead to aquifer overexploitation and GWS decline in GLB groundwater communities. We order our discussion according to analytical criteria discussed in the Methodology and indicated in the sub-section titles below.

2.5.1. Definition of the Feasible Aquifer Pumping Rate Appropriate to the Available Quantity of Groundwater in Aquifers and Geological Environmental Controls

As North American groundwater use policy is based on real property rights to waters sub-adjacent to owned land (Lusch, 2011), the same policies generally apply to manage the use of both GLB surface water and groundwater. Policies do not seem to consider that the Basin's total GWS is roughly 20 percent of total stored surface water and that groundwater is replenished at a much slower rate than surface water (USGS, 2016b). Policies also appear to insufficiently consider the different storage capacities of aquifers underlying the 186 watersheds of the Basin (Reeves, 2011) and their associated climatic and geological limits. In high-use situations, these features can lead to GWS decline.

2.5.1.1. Binational level

Although the *DLTA* and more recent international treaties have made initial steps towards the development of science-based policies to sustainably manage groundwater use in transboundary basins, the *2005 GLSWRA* and related *2008 Compact*, containing the most relevant policies for sustaining GWS, do not distinguish between physical-environmental sustainability needs of groundwater and surface water in ways that can undermine GWS sustainability.

To begin with, the quantity of groundwater withdrawal and consumption triggering regional review in the *2005 GLSWRA* and/or requiring permits per the *2008 Compact* has been criticized for being exceptionally high (Gosman, 2011). This trigger implies that lesser volumes of groundwater uses are reasonable as they do not require approval (Saunders, 2000). Given the physical-environmental limits of aquifers, the lack of consideration of the cumulative impacts of unlimited, smaller water takings on GWS can undermine its sustainability over time.

Another issue is that the *2005 GLSWRA* and *2008 Compact* state that surface water divides shall be used for the purposes of regulating new or increased diversions and high withdrawals. As watershed divides do not necessarily match aquifer boundaries (Reeves, 2011), this policy could reduce return flow to source aquifers and impede accurate monitoring of groundwater withdrawal and diversions impacts.

The third major issue is that the *2005 GLSWRA* and *2008 Compact* seem to poorly balance groundwater needs of the environment and the general public, with commercial interests represented by *NAFTA* and the coming *USMCA*. In alignment with *NAFTA's* definition of water as a product when embedded in a tradeable good, the *2005 GLSWRA* and *2008 Compact* authorise the removal of groundwater in any container measuring less than 20 litres (5.7 gallons) from the Basin. The use of groundwater embedded in products is not subject to the regulations of the *2005 GLSWRA*, *2008 Compact*, federal or state/provincial water use or conservation laws as, per *NAFTA* obligations, these laws cannot impede free trade. Worse yet, *NAFTA* is the only treaty including legal redress if water-using industries perceive barriers to free trade.

2.5.1.2. State/provincial level

While Indiana, Michigan and Ohio are the only US jurisdictions that have special policies to manage groundwater use that consider physical-environmental limits to GWS, their impact on groundwater sustainability may be debatable in high-use situations. This is because they all allow groundwater withdrawals and consumption in excess of volumetric limits requiring a permit and/or regional review set by the *2008 Compact* and *2005 GLSWRA.*

As there is less groundwater than surface water stored in the Basin, it may be argued that the water use policies set by Ontario and Minnesota may have a better effect on maintaining GWS. They are the only jurisdictions that have set stricter volumetric limits requiring a permit for withdrawal of 50,000 litres/day in any 30-day period in Ontario (*Ontario Regulation 225/14*) and 10,000 gallons/day in any 30-day period in Minnesota (*Minnesota Statutes, section 103G.801*) for both surface water and groundwater. Moreover, different standards across jurisdictions can undermine sustainable groundwater objectives as those with less restrictive regulations have a competitive advantage over others with stricter rules, thus disincentivizing the development of additional conservation policies (Burness and Brill, 2001).

2.5.2. Monitoring of groundwater levels to assess impacts of use on GWS

Responses to our standardized questionnaire indicate that institutions that permit high volumes of groundwater taking in the GLB states do not rigorously monitor groundwater levels to assess potential cumulative impacts (*Table 1*). Instead, this is done by specialized research programs in universities or the USGS. The opposite is true in Ontario, whose Ministry of the Environment issues permits for high volumes of withdrawal and consumption as well as monitors groundwater levels in its Provincial Groundwater Monitoring Network (PGMN). As the PGMN is often not appropriately placed to assist in observing cumulative impacts of groundwater taking, groundwater level monitoring can be a condition of Ontario's water taking permits.

2.5.3. *Implementation of a rigorous surveillance program to monitor adherence to groundwater use regulations*

Apart from *NAFTA*, binational policies provide no guidance on sanctioning and other actions to disincentivize non-compliance with terms of binational agreements and permits to take large volumes of groundwater. In general, the GLB states and Ontario rely on self-reporting by permitees to track compliance and water use. Additionally, except for Ontario and Minnesota, citizens who withdraw GLB groundwater volumes less than 100,000 gallons/day over a 30-day period are not required to report their pumping rates to state/provincial level water management institutions.

Pennsylvania and Minnesota are the only jurisdictions that include policies to monitor and actively disincentivize non-compliance with permits to take high volumes of GLB water. *Minnesota Statutes, Section 103G.801* requires permit holders to install flow meters to allow the Minnesota DNR to track water withdrawal. *Pennsylvania Title 32 PS 817.21 Forests, Waters and State Parks Statute* allows the Pennsylvania Department of Environmental Protection to fine permittees up to USD$5,000 for non-compliance with terms of permits. The paucity in monitoring adherence to terms of groundwater use regulations can therefore challenge proactive measures to maintain GWS, particularly in the Basin's groundwater communities.

2.6. Conclusions

Balancing the needs of the Basin's growing number of groundwater users with the complex physical-environmental considerations for sustainable yield in groundwater use policies is challenging (Kurian, 2004). Most often determined by monitoring an aquifer's groundwater level response to pumping, determining sustainable yield is difficult in the GLB because its groundwater flow systems are relatively shallow and of limited lateral extent as they consist of glacial sands and gravels. Added to the high annual precipitation of the Basin, aquifers are very interconnected with surface water bodies (Granneman *et al.*, 2000). As such, intense pumping can lessen surface water flow and even reverse flow gradients as has occurred in the Cambrian-Ordovician aquifer that has historically been pumped by high-capacity wells to supply users in the Chicago-Milwaukee metropolitan area (Feinstein, Hunt and Reeves, 2010). This adds complexity to monitoring as aquifers that have had their GWS markedly reduced by pumping can have their GWS rebound to pre-pumping levels very shortly after the end of pumping. Therefore, determining sustainable yield in the GLB can require not only monitoring of groundwater levels, as is traditionally done, but also stream flow levels.

Our findings also suggest that multilevel policies have overwhelmingly been designed based on surface water hydrology. To highlight, as of 2015, despite years of policy reform, consumptive use of the Basin's groundwater resources increased by 3 percent, while overall consumption of surface water decreased by 15 percent (Pentland and Mayer, 2015). Considered with the limited research on groundwater flow paths, storage volumes and recharge rates in the Basin (Kornelsen and Coulibaly, 2014), the lack of groundwater use policies considering the unique environmental limitations of aquifers can lead to GWS vulnerabilities in groundwater communities in high-use situations.

Additionally, the GLB's groundwater use management policies share a common trait with governments that administer large-scale, water-rich regions as they seem to inadequately balance resource conservation interests with commercial interests (Ross and Santos, 2010; Skurray, 2015).

Multilevel policies appear to treat the Basin's groundwater as an economically valuable commodity in the international trade market with benefits of maximal (not to be confused with optimal) current usage outweighing the costs of future depletion. Multilevel policies do not consider the cumulative impacts of smaller groundwater exports from the Basin in tradeable goods and containers, and there is little that national water conservation laws can do to stem this type of water loss.

While surface water and groundwater management should be interlinked per IWRM best practices, sustainable groundwater management must recognize the differences between these sub-systems of the hydrological cycle (Nelson *et al*., 2016) and capture the natural capacity of aquifers to maintain stable GWS within complex and dynamic human and natural drivers (Mollinga, 2010). In this vein, there is a clear need to develop policies specifically for the management of groundwater use that consider the unique physical-environmental factors influencing sustainable aquifer yield.

Contextualized by local socio-economic situations, areas for further consideration include (i) lower volumetric water-withdrawal triggers that require statutory permission and/or permits to take groundwater than those for surface water; (ii) rethinking rational use laws currently regulating smaller water takings in the context of their long-term cumulative impacts that can reduce GWS; (iii) prioritizing groundwater conservation in droughts; and (iv) increasing research to define aquifer boundaries, surface water-groundwater interactions, environmental-physical limits and their overall impacts on GWS quantities (Nelson *et al.*, 2016). Water resource managers would also do well to better balance the competing commercial and environmental-human interests to maintain GWS in high-use contexts, the efforts of which must address the lack of harmonization between *NAFTA*'s water trading policies and multilevel sustainable groundwater management policies.

2.7. Recommendations

A frequent cause of shortcomings in natural resource management is the mismatch of scales when institutional scales and administrative processes are ill-suited for environmental scales and processes (Borgstrom *et al.*, 2006). To address this problem, the endorsement of IWRM in the 1992 International Conference on Water and the Environment helped to mainstream watershed-scale water resource administration. The consultative principles of IWRM also helped to develop the concept of subsidiarity where smaller scale and shorter-term responsibilities are delegated to the lowest level of government with suitable capacity, with the roles of higher levels of government restricted to longer-term and larger-scale management (Stoa, 2016).

Global best practice examples show that these approaches to improving groundwater use management are only successful in certain enabling conditions. The first is a strong legal basis that clearly defines the groundwater use management roles of the different government levels. In these cases, lower level institutions are usually conferred responsibility for watershed-scale groundwater management. The role of higher-level institutions is usually limited to high level oversight and establishment of region-wide minimum standards to avoid inconsistent standards and conflicts that could occur between lower-level institutions.

The second enabling condition is a dedicated and predictable funding base for lower-level institutions given the expanded scope and highly technical nature of operations. The third is a commitment to improving technical capacities for the expanded role of lower-level institutions (Stoa, 2016). There are many successful models of this around the world (Thompson *et al.*, 2019).

To highlight, the *European Water Framework Directive* (*2000/60/EC*) commits European Union member states to achieve good qualitative and quantitative status of all waterbodies. To achieve this, the Directive establishes River Basin Districts whose jurisdictional boundaries are matched with those of watersheds, and sets minimum, regional standards that are interpreted in watershed specific River Basin Management Plans. Local authorities have the primary role in implementing these Plans, most of which have include a groundwater-use permitting system based on local hydrological conditions and sustainability needs.

In the North American context, Florida's *2013 Water Resources Act Title XXVIII, Ch. 373* established a water governance structure that may be the most complex in the United States (Stoa, 2014). Based on the recognition that an integrated approach was needed to more sustainably manage Florida's water resources; the *Act* sets up five Water Management Districts delineated according to hydrological boundaries (including transboundary political boundaries with Alabama and Georgia). The *Act* also mandates the Florida Department of Environmental Protection to have oversight of these Districts. The *Act* confers broad powers to these Districts empowering them to build infrastructure, conduct studies, develop watershed management plans, manage pollution, buy land, and most significantly, issue permits to use water. They are largely successful because of their guaranteed funding from a diverse tax base, licenses, investments and permit fees (*Florida Statutes 373.701-714*), as well as their focus on building technical capacities and clear legal basis to carry out operations (Stoa, 2014).

GLB governments have made progress in this regard, having included some IWRM principles and green paradiplomacy to improve multi-scale, cross-border water management since the 1970s (Chaloux and Paquin, 2013). Aside from the binational agreements and state/provincial level institutions to manage water quantity, Ontario has established Conservation Authorities

(CAs) whose jurisdictions are watershed-based and consist of competent administrative staff including elected municipal officials and a mix of relevant technical professions. While their roles relate to water quality and quantity monitoring, advising on best practices and protecting biodiversity, they have no direct role in groundwater use decisions and permitting.

Based on lessons from global best practice examples, the lack of inclusion of CAs in groundwater-use management misses an opportunity to leverage their inherent institutional advantages that could be useful in sustaining the GLB's GWS in high-use situations. Their advantages over state/provincial institutions include their greater institutional flexibility due to their close connection with municipal level governments. Their smaller sizes and management scales that are matched with those of watersheds also make these institutions more informed by environmental scales and processes of local groundwater flow systems. CAs also have comparable institutional competence being already engaged in monitoring and research and staffed with technical human resources (Reimann, Chimboza, and Fubesi, 2011). What is more, as they are funded by municipal levies, provincial and federal grants and special projects, there is already funding infrastructure that can be built upon for a potentially expanded role. These attributes could enable CAs to make permitting decisions, set aquifer specific use policies and respond quicker to the changing needs of local users and other environmental conditions affecting local GWS such as droughts, within Basin-wide guidelines set by state/provincial institutions for diversions, withdrawal and consumptive uses.

Regardless of the management approach chosen, fully embracing IWRM and decentralized water resource management has emerged as a best practice strategy to result in groundwater sustainability. As this has evidently not been fully embraced in the GLB, to address emerging groundwater shortage issues, multilevel institutions would do well to consider deepening the democratization of the groundwater management process and better balancing societal and ecological needs by furthering the IWRM approach.

2.8. Acknowledgements

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Appendix I

Standardized Questionnaire Distributed to State/Provincial Level Groundwater Quantity Management Institutions

Good Day,

My name is Khafi Weekes and I am a PhD student from McMaster University in Canada researching the links between groundwater sustainability and governance in the Laurentian Great Lakes Basin (GLB). I am writing to request your participation in a survey with questions designed to gain new insights on this topic and to verify the results of desk research.

The questionnaire is being administered to all GLB province/state-level water management institutions and Conservation Authorities in the Canadian side of the GLB. The Questionnaire is organized into two parts focused on: (i) groundwater monitoring and long term trends; and (ii) groundwater governance processes and policies within your jurisdictions.

I would appreciate it if you could take a few minutes to complete the questionnaire below. If you are unable to answer the questionnaire for any reason, referrals to another officer would be more than welcomed.

Thank you in advance for participation in this survey and I would appreciate it if the completed questionnaires could be returned to khafi.weekes@gmail.com or weekek1@mcmaster.ca.

Warm Regards

Khafi Weekes

QUESTIONNAIRE

Part 1: Groundwater Quantity Monitoring and Long Term Trends

1. Does your institution collect historical groundwater extraction and/or groundwater use data?
2. Does your institution monitor groundwater levels within its jurisdiction?
3. Are there any aquifers within your jurisdiction that are experiencing major, long-term groundwater decline?
4. If Yes to Question 3, please indicate whether or not there are GLB aquifers within your jurisdiction that have experienced or are currently experiencing the following indicators associated with groundwater over-pumping and decline. If ‘’Yes’’ to any of the indicators below, please provide a short summary of the situation (location, duration, magnitude of problem etc.). The indicators are as follows:

- Upwelling of deeper brines with pumping.

- Collapsing cavities in evaporites due to dissolution induced by faster water flow rates with pumping.
- Land subsidence as pumping reduces pore water pressure.
- Reduced stream water levels as baseflow from groundwater outflows are reduced due to pumping.
- Damage to groundwater-dependent ecosystems such as riparian vegetation, cave dwelling. animals and cold water fisheries due to reduced ecological flows with pumping.
- Long-term decline of groundwater table levels due to pumping.

Part 2: Groundwater Quantity Governance

1. Does your state/provincial level government have policies governing groundwater extraction and use that set stronger groundwater conservation safeguards than those set by the state or provincial government?
2. If yes to Question 1, can you list these laws and policies?
3. To the best of your knowledge, are there any policies or laws governing groundwater management in your jurisdiction that are unique compared to other groundwater policies of other jurisdictions within the GLB?
4. Are municipal governments or watershed management organizations (e.g. Conservation Authorities) in your state/province consulted regarding requests for permits to take water or bulk water uses?
5. If yes to Question 4, do you believe consultation with your municipality is sufficient?
6. Do municipal governments or or watershed management organizations (e.g. Conservation Authorities) in your state/province have a role to play in monitoring groundwater extraction volumes?

The results of this questionnaire are intended to orient a PhD researcher from McMaster University to access relevant publicly-available information. Under no circumstance will private data from questionnaire participants be collected. Participation in this questionnaire is voluntary.

3. CHAPTER 3

Weekes, K. and Krantzberg, G. (Submitted for Publication). "Twenty-first Century Science Calls for Twenty-first Century Groundwater Use Law: A Retrospective Analysis of Transboundary Governance and Future Implications in the Laurentian Great Lakes Basin." *Water*, 13(13):1768. DOI: 10.3390/w13131768.

ABSTRACT

How has groundwater use been historically governed by multilevel jurisdictions across the Laurentian Great Lakes Basin (GLB)? To what extent have they contemplated the physical-environmental requirements to maintain aquifer storage in devising policies and making decisions governing groundwater use? Although it is the largest freshwater store in the globe, cases of groundwater shortages are increasingly being reported across GLB communities, raising questions on the fitness of multilevel governance approaches to maintain groundwater storage (GWS) with growing climate and human pressures. Applying retrospective analytical methods to assess the US and Canada's century-old collaboration to maintain GLB water quantities, we characterize long-term trends and undertake systematic diagnosis to gain insight into causal mechanisms that have persisted over the years resulting in current GWS governance gaps. We reveal the surprising prominence of policies intended to safeguard surface water quantities being used to govern groundwater use and thereby maintain GWS. We also connect these, based on sustainable aquifer yield theory, to growing groundwater insecurity in the Basin's drought-prone and/or groundwater-dependent communities. Based on deep understanding of long-standing policy pathologies, findings inform transboundary GWS governance reform proposals that can be highly useful to multilevel government policy-makers.

3.1. Introduction

With estimates ranging from 5,585 km^3 to 4,000 km^3 (Coon and Sheets, 2006), groundwater accounts for roughly 20 percent of water stored in the Laurentian Great Lakes Basin (GLB). Groundwater fluxes maintain habitats and baseflows to tributaries of the five (5) Great Lakes (GLC, 2016). It has become increasingly vital for society, supporting the US $6 trillion regional economy (Kavcic, 2016) of the eight US states and the Canadian province of Ontario that are within the GLB's hydrological boundaries (*Figure 4*). Rising populations, water demand and climate change (Lofgren, Hunter and Wilbarger, 2011) are driving an emerging problem of groundwater storage (GWS) decline. At the Basin-scale, long-term satellite monitoring estimates an average GWS loss of 3.8 ±2.3 km^3/year (Huang *et al.*, 2010). Though this rate of decline pales in comparison to the overall water-richness of the GLB, the globe's largest freshwater store, much of it occurs in drought-prone and/or groundwater-dependent communities. Located further inland, these locales are without ready access to Great Lakes' waters and are becoming increasingly water insecure (Howard and Gerber, 2018).

Figure 4: States and Provinces within the Laurentian Great Lakes Basin Boundary (*Source: NOAA, 2004*)

The above highlights the need for GLB governments to provide policies and decision-making standards guiding management actions (Megdal *et al.*, 2014) that proactively address human and climate drivers of GWS depletion (Dellapenna, 2014). It also presents an opportunity for proactive measures halting further proliferation of this problem. Given its transboundary basin settings, policies and standards (aka the 'GWS governance framework') are contained in binational to municipal level statutes, voluntary agreements/regulations, common law and treaties (Granneman and Van Stempvoort, 2016). Per North American institutional historicism, the most important to maintaining GWS are those directly controlling groundwater use: out-of-basin diversions, pumping rates, allocation, conservation, consumption, and withdrawals (Kreutzwiser, Durly and Priddle, 2013). Economic policies are also key, creating fiscal deterrents and/or incentives under which groundwater use decisions are made (Mayer, Mubako and Ruddel, 2016). Environmental safeguards are another aspect, with requisites for data collection and monitoring as well as technical/environmental standards for well construction and pumping (Kemper, 2007).

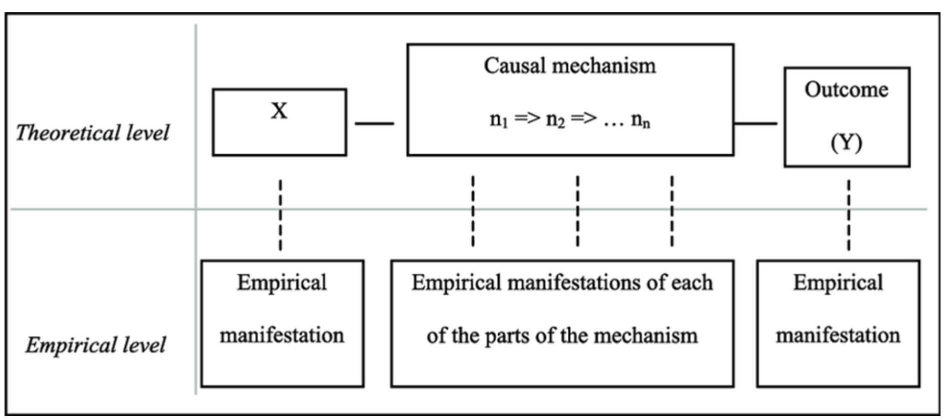
Considering worsening GWS outcomes, researchers have long posited that the governance framework may be unfit for purpose in high-groundwater-stress contexts (Hodge, 1989; Saunders, 2000; Karkkainen, 2013; Dellapenna, 2014; Rivera, 2015; Weekes, Krantzberg and Vizeu, 2019). They concur on its inadequate reflection of aquifers' physical/environmental needs to maintain GWS; and insufficient guidelines and incentives promoting conservation and efficient uses. Retrospective analysis of historical governance characteristics has proven useful to deepen understanding of present-day policy gaps, and confirming inferences of why policies led to current environmental outcomes (Nelson and Quevauviller, 2016). Using this analytical approach, we deconstruct the historical evolution of GWS governance, deducing features and inferring causal linkages that are likely to have culminated in growing cases of GWS decline and gaps in the current

GWS governance framework. Findings are used to proffer recommendations of governance reforms addressing the growing spectre of groundwater insecurity deepening in vulnerable locales.

3.2. Materials and Methods

We applied Causal Process Tracing (CPT) - a qualitative, retrospective analytical technique useful for deducing change and causation within a temporal sequence of events (*Figure 5*; Beach, 2016). Per *Figure 5*, CPT operates by characterizing the intervening Causal Mechanism (n_1=> n_2=> etc.) between the Cause(s) (*X*) and the Outcome(s) (*Y*). The Causal Mechanism is a chain of events or 'Empirical Manifestations' (n_x) linking Causes (*X*) with their long-term effects and eventual Outcomes at the end of the study period (*Y*). It describes "not simply a relationship that has been found, but one that has been found repeatedly" (Waltz *et al.*, 1979). As such, the more Empirical Manifestations that are observed within the study period, the more confident researchers can be of the Causal Mechanism (Beach and Pedersen, 2019). Thereby, CPT depends on detailed descriptions of Empirical Manifestations as well as the concepts linking and/or used to diagnose them, which are based on the overall hypothesis and theories of how *X* impacts *Y*.

Figure 5: Elements of the Causal Process Tracing Method (*Source: Beach and Pedersen, 2019*)



At its core, our research is a historical process narrative explaining how GWS governance gaps are likely to have persisted over time to feature in current governance and lead to groundwater insecurity. In this context, CPT was applied to design our analysis as outlined in *Table 6*.

Table 6: Causal Process Tracing Application in Research Design

CPT ELEMENT	**APPLICATION IN RESEARCH**
Cause (***X***)	Foundational policies and decision-making standards of the current GWS governance framework.
Outcomes (***Y***)	• Persistent GWS decline in drought-prone and/or groundwater-dependent GLB communities. • Weaknesses and gaps in the present-day GWS governance.
Causal Mechanism	Multilevel governance processes, that have evolved over time, defining groundwater uses and environmental safeguards relevant to maintaining GWS.
Empirical manifestations (n_x)	Milestones and/or changes in policies and decision-making standards over the timeframe of the evolution of the GWS governance framework e.g., successive binational treaties, statute amendments, major court decisions and other governance mechanisms influencing GWS.
Causal Linkages ((n_1=> n_2=> etc.)	Established by interpretation and detailed descriptions of policies and decision-making standards over time based on the hypothesis and sustainable aquifer yield theory.

We first characterize the Outcomes, providing an overview of GWS governance weaknesses and the emerging problem of groundwater insecurity. Drawing from official government reports and published literature, we characterize the emerging GWS decline problem, documenting cases at the sub-watershed scale, using a wide range of indicators including: (i) deteriorating water quality with oxygen exposure to lithology (Farid *et al.*, 2019) and/or upwelling of deeper brines as well water levels reduce due to over pumping (Pophare *et al.*, 2014); (ii) collapsing cavities in evaporates (e.g., gypsum) due to dissolution as pumping increases water velocity and/or land subsidence due to over pumping that reduces pore water pressure causing gradual lowering of land (Yong *et al.*, 2018); (iii) waning stream levels as baseflow declines

(Barlow and Leake, 2012); (iv) loss of groundwater-dependent ecosystems (Custodio, Kretsinger and Llamas, 2005); and (v) sustained decline of water table levels, defined as the upper limit of the underground where all interstices and voids are saturated with water (Scanlon *et al.*, 2012). Data on these indicators were sourced from desk studies of publicly available reports from GWS governance institutions, and responses to our survey distributed from December 2018 to February 2019 to managers in these institutions. We received a 100 percent response rate.

To deduce the Cause and Causal Mechanism, the evolution of groundwater use policies and environmental safeguards impacting GWS were studied over the introduction of common law principles in the late 19th century, up to the adoption of the *2005 Great Lakes-St. Lawrence Basin Sustainable Water Resources Agreement* (*2005 GLSWRA*), the most recent binational agreement controlling groundwater use. Economic policies impacting GWS were reviewed up to the *2020 US Mexico Canada Agreement* (*2020 USMCA*). This study period is sufficient as legal concepts foundational to current GWS governance are drawn from 19th-century common law (judge-made case law long applied by appellate courts to resolve legal disputes related to groundwater use and conservation; Expert Panel on Groundwater 2010). From this, multilevel treaties, rules and statutes (laws made by legislative bodies of multilevel governments) have evolved over the years (Nelson and Quevauviller, 2016). As policies and standards component to the present-day GWS governance framework have not changed significantly since the *2020 USMCA* and *2005 GLSWRA* (Weekes, Krantzberg and Vizeu, 2019), they were considered appropriate for delimiting the study period. Data on historical policies and standards component to the Cause and Causal Mechanism were sourced from peer reviewed publications, expert interviews, as well as publicly available government repositories and archives. Policies made by municipalities were not considered as they are not involved in GWS policy and decision-making (Weekes, Krantzberg and Vizeu, 2019).

Identification of empirical manifestations and linkages within the Causal Mechanism were based on sustainable aquifer yield theory. Aimed at avoiding undesirable social, environmental and legal outcomes from aquifer pumping, the theory posits a balanced compromise between the contrasting strategies of either little to no pumping of aquifers, or the total uptake of natural discharge (Walton and McLane, 2013). Balancing these opposing governance strategies is typically based on consideration of the physical/environmental requirements for maintaining GWS that are component to sustainable aquifer yield (Lin and Lin, 2019; Freeze and Cherry, 1979). We applied these as evaluative indicators to identify and assess scopes of policies and standards, pinpointing their changes over the study period, and determining the extent to which they considered: (i) the finite volume of groundwater that aquifers can store that is innately limited by their geophysical parameters; (ii) natural recharge of aquifers that are controlled by precipitation and climate; (iii) fluxes required to maintain vital environmental functions; and (iv) whether allowed human uses disturbed the equilibrium required to sufficiently maintain GWS while avoiding unwanted outcomes.

To conclude, we synthesized findings, diagnosing the extent to which historical policy gaps have carried over to the current GWS governance framework; and the governance processes by which weaknesses have persisted over time. Insights were then used to link historical governance to emerging GWS decline cases, as well as provide recommendations to address governance gaps.

3.3. Results

3.3.1. Outcomes (Y): the emerging problem of groundwater insecurity and linked governance gaps

- <u>*Characterizing Sub-Watershed Scale GWS Decline*</u>

Though incidence of over pumping and resulting GWS decline indicators have not yet been comprehensively studied in the GLB, emerging reports point strongly to them being related to communities that are drought-prone and/or are heavily reliant on the resource. Based on available information of the incidence of GWS decline, most documented reports were found in Michigan, the only state/province wholly within the hydrological boundaries of the GLB.

` The impacts of over-pumping on GLB stream baseflow and groundwater-dependent ecosystems are poorly understood (Granneman and Van Stempvoort, 2016). However, one well documented case in Wisconsin linked excessive pumping to the drying of wetlands causing native habitat loss and invasive species spread (GLEC 2019). Better documented are cases of long-term pumping reducing riverine baseflow. Groundwater contributes from 48 percent of streamflow in the Lake Erie Sub-Basin up to 79 percent in the Lake Michigan Sub-Basin (Holtschlag and Nicholas, 1998). Another report documented is the case of over-pumping not only reducing baseflow to watercourses but reversing water flow from surface waters to aquifers supplying the Chicago-Milwaukee metropolitan area, Green Bay, Wisconsin and Toledo, Ohio (Granneman *et al.*, 2000).

Dominated by karsts and glacial, unconsolidated deposits, the Basin is susceptible to land subsidence induced by over-pumping (Keqiang, Liu and Wang, 2003). Subsidence has been mapped in west Michigan, north Wisconsin and north Minnesota that are within the Basin (Galloway, Jones and Ingebritsen, 2000). GLB municipalities having high risks of gypsum cavity collapse linked to mining dewatering were documented in Ontonagon, Houghton, Iosco, Keweenaw, Kent, Barry, Eaton, Calhoun, and Jackson counties in Michigan (Pereira, 2017). Upwelling of brines due to excessive mine dewatering has been reported in wells in the townships of Windsor and Romney, Ontario (Granneman and Van Stempvoort, 2016). In Michigan, upwelling of brines due to long-term pumping for drinking water and agriculture has been well documented in Michigan's Lower Peninsula (Curtis, Sampath and Liao, 2015), as well as in Ottawa County that abuts northern Lake Michigan (Curtis, Liao and Li, 2018). Arsenic concentrations exceeding the US Environmental Protection Agency's maximum contaminant level of 10 μg/litre are often reported in well water in Southeast Michigan (Asher *et al*., 2017) in the counties of Huron, Tuscola, Sanilac, Lapeer, Genesee, Shiawassee, Livingston, Oakland, Macomb, and Washtenaw. These wells pump the Marshall Sandstone, a basement aquifer. Relatedly, long-term pumping has caused drinking water of the straddling community of Waukesha, Wisconsin to be contaminated with radium (Choi *et al*., 2012), prompting its successful application for access to GLB water resources.

Responses to our survey (*Appendix I*) indicated that persistent groundwater table decline occurs in aquifers supplying roughly 10 percent of GLB municipalities. Widespread groundwater table decline risks have been modelled in Michigan including the Grand Rapids and the metropolitan area of Detroit and its eight suburban counties including Genesee, Oakland, Macomb, Washtenaw, Wayne, St. Clair, Lapeer and Monroe (communication from the Department of Environmental Quality on December 5, 2018). This has also been extensively documented in aquifers supplying Milwaukee and Chicago including its eight eastern suburban counties as intense pumping beginning in 1864 caused groundwater table levels to decline by as much as 275 meters by 1980 (Reeves, 2011). In the Ontario sub-Basin, aquifers supplying municipalities in the Grand River Watershed, including Kitchener, Waterloo, Cambridge, the City of Guelph and surrounding townships have a moderate risk of developing GWS shortages (GRCA, 2019). These risks are particularly in droughts, the summer agricultural growing season, and periods of high municipal water demand used to supply the residential, industrial, commercial sectors (Bruneau, Dupont and Renzetti, 2013).

- *Characterizing Present-Day GWS Governance Weaknesses*

Incorporated into current federal and state/provincial laws, many of the current policies and decision-making standards governing groundwater use are from the binational *2005 GLSWRA.* Aimed at sustaining the quantity of all GLB waters, it generally prohibits withdrawals over 379,000 litres/day "in any 30-day period (including Consumptive Uses) from all sources" (defined as bulk water); or diverting any volume of water from the Basin, except when in containers measuring 20 litres or less, without a regional review decision-making process by Great Lakes governors/premiers. Parties are urged to promote efficient water use and to record water uses by sector in a regional database. Water uses below bulk water definitions are considered "reasonable uses" for which GLB states/provinces can set their own regulations. The Great Lakes states passed a series of *Great Lakes-St. Lawrence Basin Sustainable Resources Compact Acts* into law between 2007 and 2008; and Ontario brought these policies into effect in *Ontario Regulation 225/14* in 2014. These laws limited the scope of the *2005 GLSWRA* regional review process to deciding on large water diversions from the GLB, and gave the states/province responsibilities to regulate bulk water use; the most common regulation being the Permit to Take Water (PTTW) programs.

Relevant economic policies include the 2020 *USMCA*, state/provincial PTTWs and/or well license fees, and municipal water supply tariffs. As the newest North American free trade treaty, the *2020 USMCA* allows export of GLB groundwater when embedded in products. It furthers the scope of past trade agreements, including large, medium and small enterprises and removes tariffs on a wider range of agricultural products. It is the only binational agreement impacting GWS with legally binding recourse should enterprises perceive unfair barriers to free trade (Larsson, 2015).

With identical policies guiding groundwater and surface water use, as well as the same high volumetric water use thresholds for bulk water definitions, multilevel governments overlook fundamental physical/environmental differences between groundwater and surface water (Howard and Gerber, 2018). Sustainable aquifer yield considerations also appear to be largely ignored in federal and state/provincial governance of smaller volumes of GLB groundwater use (Sterner *et al.*, 2017). Some examples are that policies generally do not include volumetric limits controlling groundwater pumped for agricultural purposes or from smaller-capacity wells on private land for domestic use. Policies guiding aquifer pumping in federal lands are also largely absent (Expert Panel on Groundwater, 2010). Instead government oversight is typically limited to data recording requirements and technical specifications for commissioning wells (Kreutzwiser, Durly and Priddle, 2013).

Economic policy tools generally encourage groundwater overuse, furthering groundwater insecurity risks in vulnerable locations (Burton *et al.*, 2010). The *2020 USMCA* increases competition for groundwater resources by opening up free trade provisions to a greater pool of enterprises. The removal of trade tariffs on a wider set of agricultural products increases pressure on aquifers, given that agriculture is the most intense water consuming sector within the GLB. At the state/provincial level, higher capacity wells requiring PTTWs attract low permit fees (Kreutzwiser, Durley and Priddle, 2013); and groundwater used for agriculture and firefighting are exempt from permits (IJC, 2010). Finally, graduated block rates of municipal water supply tariffs can incentivize water wastage, as rates become progressively cheaper the more water is used (CEC, 2017).

3.3.2. Causal mechanisms: linking historical GWS governance to current outcomes

- <u>*Fundamental Legal Principles Underpinning the Evolution of GWS Governance*</u>

In North America, controlling who has access to groundwater has historically been tied to land ownership (Nelson and Quevauviller, 2016). As the flowpath of groundwater was considered to be less obvious than surface waters (Gardner *et al.*, 2009), English common law devised the *Absolute Ownership Rule* allowing landowners to use groundwater below their property without limits or obligations to conserve the resource for neighboring and future uses (McKay, 2007). Through colonization of North America, this was modified to the *Reasonable Use Rule*, limiting groundwater uses to those done without waste or harm to neighbors (National Research Council, 2007). In the GLB, reasonable use was nuanced by the *Underground Stream Doctrine* that interrelates surface water and groundwater rights of use, applying the *Riparian Doctrine* or *Surface Water Rule* to govern GWS (Kreutzwiser, Durley and Priddle, 2013). Herein, wells are treated as surface diversions and groundwater flow considered 'tributary' to surface waters, with the aim of conserving groundwater being inherently *for the purposes of* preserving surface water resources.

- <u>*The Evolution of Binational GWS Governance*</u>

As far back as the *1794 Jay Treaty* aimed at maintaining Great Lakes' levels for international navigation during the Napoleonic wars, binational governance of GLB water uses has prioritized maintaining surface water quantities (National Research Council, 2007). Modern governance began with the *1909 Boundary Waters Treaty* (*1909 BWT*) that generally banned large diversions of surface waters straddling the international border. With the aim of ensuring equitable "domestic and sanitary uses, navigation uses, and uses for power and irrigation" it established the International Joint Commission (IJC) for enforcement. However, its GWS role was not formalized until after the 1988 Cabin Creek Coal Mine case when the IJC's *Water Use Reference* was updated, allowing investigation of groundwater issues as a matter of practice (IJC, 1988).

The next significant binational agreement on GLB water use was the *1956 Great Lakes Basin Compact* that created the Great Lakes Commission (GLC) to promote "orderly, integrated, and comprehensive development, use, and conservation" of GLB water resources. It was the first agreement to adopt a whole of basin approach to governance, explicitly considering the range of water uses: "industrial, commercial, agricultural, water supply, residential, recreational, and other." Despite these advances, its mandate was limited to the Great Lakes and all interconnected "rivers, ponds, lakes, streams and other watercourses," thus excluding GLB groundwaters.

Another important update to governance was the *1985 Great Lakes Charter* (*1985 Charter*). Established as a good faith agreement between the GLB governors and premiers, it contained standards and policies for the uses of "all GLB waters" that for the first time included groundwater in its definition. It expanded GLC membership to include Canadian premiers and introduced the regional review process for making decisions on bulk water use and diversions. It was also the first to define bulk water use as any withdrawal exceeding 380,000 litres/day in any 30-day average, and generally ban any new or increased diversions and consumption of water uses exceeding 19 million litres per day in any 30-day period without consent via regional review. It also initiated the establishment of Great Lakes Regional Water Use Database. As the *1985 Charter* was set up as a non-legally binding agreement, it did not include enforcing mechanisms. Thus, the GLC later agreed to the *2001 Great Lakes Charter Annex* (*2001 Annex*), committing the GLB states/province to agree on policies to be included in state/provincial laws within the next three years, enabling binational policy prescriptions to become legally binding.

Despite these policy advances, the *1985 Charter* did not keep pace with groundwater science (Hammer, 2018), entailing identical guidance for bulk groundwater and surface water definitions and recommendations to govern its uses. Appearing not to reflect on groundwater's relative scarcity and lower replenishment rates compared to surface waters, it also stated its overall aim as safeguarding surface waters. In addition, although the 1985 Charter initiated the launched of the Regional Water Use Database in 1988, and it has been providing yearly reports on water withdrawals, consumption and diversions from the GLB, it has not had a specific data field for tracking water use from groundwater sources. This makes it difficult to garner consistent information on groundwater use, an essential data input for determining sustainable aquifer yield. In fulfilling the commitment for a legally binding agreement with the *2005 GLSWRA*, these GWS governance gaps remained unchanged.

Though relevant binational economic policies can be traced back to the *1855 Reciprocity Treaty*, it was not until 1987 that the first was established that had direct impact on maintaining GWS when both countries established the *Canada-United States Free Trade Agreement*. Superseded by the *1994 North American Free Trade Agreement* that admitted Mexico to the free trade zone, these agreements followed the General Agreement on Tariffs and Trade of the World Trade Organization. Herein, GLB groundwater and surface water were allowed to be exported when “captured whether in bottles, tankers or pipelines.” Overlooking the cumulative impacts this can have over time, and without environmental safeguards for aquifers, these agreements included settlement mechanisms for trade disputes. This opened the door to growing competition and conflicts between conservationists and industries drawn to the Basin by its cheap, clean and abundant groundwater supply (Bakker and Cook, 2011).

- *The Evolution of Federal GWS Governance*

Per the *1867 Canadian Constitution*, the Canadian federal government has had a historically limited role controlling groundwater use, limited to aquifers within international borders and those underlying railways, federal and First Nations lands. However, it has long facilitated aquifer mapping and tracking GWS levels, founding the Geological Survey of Canada (GSC) in 1947 and expanding its groundwater research commitments in the *1987 Federal Water Policy* (Nowlan, 2007). The US federal government has also long backed research, founding the US Geological Survey (USGS) in 1879. However, it has had a more central GWS governance role with the *Commerce Clause* of the *1787 United States Constitution* and the *1986 Water Resources Development Act* (*1986 WRDA*) prohibiting diversions of all US waters without Congressional consent. A 2000 amendment to the *1986 WRDA* banned all diversions of GLB water unless approved by Great Lakes governors, thus conferring the GLB states' GWS governance role (Leshy, 2008).

- *The Evolution of State/Provincial GWS Governance*

Most GWS governance roles have long rested with the eight GLB states and Ontario. After agreeing on the *1956 Great Lakes Compact*, states/province adopted bulk water use and diversion counsels of successive binational agreements. In so doing, they have also followed the historical trend of overlooking sustainable aquifer yield requirements, favoring surface water preservation objectives. On regulating smaller volumes of GLB groundwater use, there has been considerable variation in policies and decision-making standards across state/provincial governments (Kilbert, Merkle and Miller, 2019). This is the focus of our assessment below. On court rulings, unless otherwise stated, all states/province applied the *Underground Stream Doctrine/Reasonable Use Rule* to resolve groundwater use conflicts. As the only state wholly within the Basin's boundaries, we focus analysis on court decisions impacting GWS in Michigan. Its many landmark court rulings demonstrate well how groundwater conflict resolution has been historically treated in case law.

– <u>*Ontario*</u>

Ontario has had some of the earliest GLB policies in place impacting GWS. Its *Ontario Water Resources Act* (*OWRA*) included licensing and pumping rate data collection requisites since 1961 (Nowlan, 2007). A 1990 *OWRA* amendment introduced more stringent requirements for bulk water use than the *1985 GLC*. It required permits for taking over 50,000 litres per day, environmental impact assessments (EIAs) and a graduated approach to PTTW fees. Reflecting consideration of lower quantities and replenishment rates of GWS, fees ranged from none for taking water from low environmental impact sources, to $3000 for groundwater PTTWs issued in a high-use regions and/or for water bottling purposes (*Section 34*). The *2001 Ontario Municipal Act* was the only policy of all GLB states/province mandating inclusion of municipalities in PTTW decision-making. On regulating pumping from both small and high-capacity wells, a 2002 *Safe Drinking Water Act* amendment mandated tracking of pumping rates to avoid uptake of brines, thus reducing aquifer over-pumping risks. The *2002 Ontario Low Water Response Act* added a temporal dimension to GWS governance, setting progressive restrictions on water pumping from small and high capacity wells corresponding to reducing levels of streamflow and/or precipitation in times of drought.

– <u>*Pennsylvania*</u>

Far stricter than most GLB states/provinces, in Pennsylvania there has been long-standing consideration of cumulative impacts of smaller water takings (even from aquifers underlying private property), temporal limits to groundwater use, and focus on EIAs before granting bulk groundwater permits. The earliest Pennsylvania statute impacting the Basin’s groundwater quantities was the *1956 Water Well Drillers License Act* (32 P.S. §645.1 et seq) which required users to request and renew annual licenses for small and large capacity wells and reporting of water table levels. The *1978 Emergency Management Services Code* (35 Pa.C.S. §7101 et seq.) was the first GLB policy to mandate reduced groundwater use during droughts. Though Pennsylvania did not require permits for bulk groundwater withdrawals in private properties prior to the *2005 GLSWRA*, the *1984 Safe Drinking Water Act* did appear to consider sustainable aquifer yield. The only state to do so within the study period, it empowered municipalities to issue permits, at an annual fee capped at $500.000, for persons taking groundwater from publicly owned aquifers. It also required EIAs on aquifers as part of groundwater permit requests. The *2002 Water Resources Planning Act 220* (27 Pa.C.S. Chapter 31) made it compulsory to report groundwater withdrawals for domestic use from aquifers within private land when exceeding 10,000 gallons per day.

– *Minnesota*

Minnesota has had a tradition of having little to no regulations for the use of groundwater within private land, rather focusing on the protection of groundwaters and surface waters within publicly owned lands. In 1897, *Minnesota Water Law* first adopted the term public waters (Minnesota Water Law Section 103). However, groundwater was excluded in the original definition of public waters, instead limiting public waters to large lakes and streams that were capable of beneficial public uses such as water supply, fishing and boating. All other waters were deemed private and beyond the regulation of the state. The catastrophic drought of the mid-1930s demonstrated the need for more stringent protection of groundwater and surface waters, and the *Minnesota Water Law* was amended empowering the state to issue permits to protect the public's interest in the amount of water available for use. Permits were also required for large quantity uses of public waters as well as for the appropriation of public waters for agricultural, industrial and commercial sectors. Beginning then, the permit fee structure has remained the same for groundwater and surface water, without any other inducements to encourage more judicious groundwater use.

In 1976, the *Public Waters Inventory Program* was established (Laws of Minnesota 1976, Chapter 83 and Laws of Minnesota 1979, Chapter 199) reiterating the definition of public waters as those serving "beneficial public purpose" and for the first time including waters for the recharge of aquifers as public waters. A 1979 amendment confirmed the location of public waters as those within lands to which the State of Minnesota or the federal government hold title. It also made it mandatory for all 87 counties of Minnesota, including the ones to the north east within the GLB, to participate in the public waters inventory. The *1990 Allocating and Controlling Waters of the State* (Laws of Minnesota 1990. 103G.255) amended several previous laws to provide further clarity on the state's role in conserving sufficient water resources for public use, however it did not include specific, hydrogeological science-based actions for conserving groundwater. For the protection of groundwaters within private lands, in 1990, in response to the 1987–1989 drought, the state developed a non-legally binding *Minnesota Statewide Drought Plan*. Still used today. It consists of a set of prescribed local action responses to five different conditions/phases of climate (normal to extreme drought).

– *Wisconsin*

Although unlike Ontario and Pennsylvania, Wisconsin had no laws mandating drought responses during the study period, it had amongst the more comprehensive water use and aquifer protection policies of GLB states/province. The *1983 Comprehensive Groundwater Protection Act 410* (Chapter 160, Wisconsin Statutes) established the Groundwater Coordinating Council (GCC) to assist state agencies' coordination of water conservation and provide GWS scientific data. On smaller capacity wells, it empowered municipalities to regulate- under Wisconsin Department of Natural Resources (DNR) supervision- construction and pump installation for some private wells. The *2003 Groundwater Protection Act* (Wisconsin Act 310) mandated EIAs before granting

PTTWs for high-capacity wells. The *Act* also defined the spatial extent of Groundwater Management Areas, mandated pumping rate reporting and established a decision-making standard for addressing water quantity issues in rapidly growing areas of the state. However, with annual PTTW fees set at $100 for both surface water and groundwater, there did not seem to be reflection on their relative quantity and recharge disparities (Kent and Dudiak, 2001).

– *Indiana*

Indiana's approach to GWS governance featured some of the least physical/environmental considerations for protecting GWS as a natural resource of all GLB states/province within the study period. Since 1860, Indiana has applied the 'Reasonable/Beneficial Use system' to govern both surface water and groundwater uses (Eckstein and Hardberger, 2017). Like Minnesota, its application of the *Reasonable Use Rule* in the Indiana Code (IND. CODE § 14-25-7-6.) permits "the use of water for a beneficial use in such quantity and manner that is: (1) necessary for economic and efficient utilization, and (2) is both reasonable and consistent with the public interest." This interpretation of reasonable uses carried through to the first statute providing some protections to GWS, the *1985 Emergency Regulation of Ground Water Rights* (IC 14-25-4), that protects owners of small capacity wells from the impacts of high capacity wells if it significantly lowers their GWS levels. This has been further reinforced in Indiana case law that has held landowners liable for all types of damages caused by the excessive removal of groundwater, including subsidence damage. This is illustrated in the 1998 Indiana Court of Appeals ruling against the GLB City of Valparaiso. Damages were awarded to the plaintiff for land subsidence caused by the City's over-pumping of GLB ground-water (City of Valparaiso v. Defler, 694 N.E.2d 1177, 1180-82). The Court of Appeals stated that reasonable and beneficial use of groundwater must be maintained to avoid harming the rights of adjacent landowners.

In 1994, Indiana established a *Water Shortage Plan* including environmental indicators of water shortages and management responses. Although the plan was the first towards protecting GWS in drought situations in the state, similar to Minnesota, it lacked enforcement mechanisms being entirely voluntary. Another significant policy was the *2003 Water Rights and Resources Act* (Indiana Code 14-25-1(1)). While it defined the types of water subject to government protection for the public welfare, it did not include groundwater.

– *Michigan*

Prior to the passage of the *2005 GLSWRA*, Michigan's statutes have largely omitted standards or volumetric controls of groundwater use (Lusch, 2011). Instead, these matters have largely been handled by courts ruling on groundwater complaints applying the *Reasonable Use Rule*. Damages awarded to plaintiffs have historically omitted measures to conserve GWS or to encourage efficient use, instead being primarily concerned with ensuring equitable groundwater access rights. The earliest of these rulings was from the Michigan Supreme Court in the 1917 *Schenk v. City of Ann Arbor* case (196 Mich 75, 163 NW 109) where it was found that the City of Ann Arbor did not have more rights to withdraw groundwater for the provision of public water supply than a private landowner. The court also ruled on another landmark case, *Bernard v. City of St. Louis* in 1922 (220 Mich 159, 189 NW2d 891) in favor of the plaintiff, requiring the City of St. Louis to reduce groundwater withdrawals to maintain adequate water for the plaintiff's use, and awarding compensation for pumping equipment that the plaintiff had to install. In 1982, the Michigan Court of Appeals reaffirmed the outcome of *Bernard v. City of St. Louis*, ruling similarly in the *Maerz v. U.S. Steel Corporation* case (116 Mich App 710).

Statutes that did cover GWS were first established in the late 1970s, however, they largely carried over the *Reasonable Use Rule* typically applied by courts to resolve groundwater use complaints. Reinforcing that municipal governments had no authority to curb groundwater uses was the 1978 *Michigan Public Health Code* (PA 368, MCL 333.1101 to 333.25211) stated "a local unit of government shall not enact or enforce an ordinance that regulates a large quantity withdrawal." Another was the 1981 *Michigan Right to Farm Act* (P.A. 93 Sec. 3 (3)) that listed conditions that offered farmers protection from nuisance suits. Noting that it cannot be applied to resolve water use conflicts, the Act precluded installation of new irrigation equipment or new technologies as grounds for groundwater use complaint suits, paving the way for installation of higher capacity pumps adding pressure on aquifers. The 1994 *Natural Resources and Environmental Protection Act 451* (Mich. Comp. Laws § 324.30106) was unique in that it was the first to have provided some GWS protection, requiring EIAs before granting permits. The *2003 Aquifer Protection and Dispute Resolution Act* sets withdrawal thresholds based on a regional groundwater model that can classify aquifers as overexploited.

Michigan's past court rulings have also had implications on the extent of application of free trade treaties prior to the *2020 USMCA*. The Michigan Court of Appeals 2005 ruling on the *Michigan Citizens for Water Conservation v Nestle Waters North America Incorporated* (269 Mich. App. 25, 709 N.W.2d 174) is one of the most significant cases. Nestle had previously purchased groundwater rights to a Sanctuary Springs property in Mecosta County, established four high capacity wells on site pumping groundwater at a rate of 400 gallons per minute (576,000 gallons per day). The *1994 Natural Resources and Environmental Protection Act 451* was used as a basis for ruling on the application of Michigan Citizens for Water Conservation (MCWC) to prevent Nestle from continuing operations. Considering the MCWC as riparian property owners negatively affected by Nestle's wells, the court found that Nestle's withdrawals unreasonably interfered with MCWC's rights. The court also noted the harmful impacts Nestle's groundwater extraction was having on the adjacent wetlands and watercourses including destroying fisheries habitat, and impairing its ability to filter water, control erosion and flooding. The court ordered Nestle to cease operations pending determination of more equitable groundwater withdrawal rate allowing consideration of sustainable aquifer yield factors.

It was not until the 2006 amendment to the *1994 Natural Resources and Environmental Protection Act 451* and the *Safe Drinking Water Act* that any statutes were passed that regulated the removal of any quantity of GLB groundwater from an aquifer for commercial purposes. Although persons can withdraw any quantity of groundwater without cost in Michigan except for the well-extraction fee of USD $200/year, EIAs on aquifers became one of the requirements for requesting bulk groundwater uses. The Michigan Department of Environmental Quality (*PA 37*) required this for “A person who proposes to engage in producing bottled drinking water from a new or increased large quantity withdrawal of more than 200,000 gallons of water per day from the waters of the state or that will result in an intrabasin transfer of more than 100,000 gallons per day average over any 90-day period.” Although these recent policies constitute a step in the right direction allowing institutions and courts to consider volumetric limits to sustainable aquifer yield in issuing permits and determining reasonable uses in groundwater use conflicts, respectively, conflicts between GWS conservation and economic interests are expected to continue (Miller, 2008).

– <u>*New York*</u>

Prior to the *2005 GLSWRA*, New York statutes controlling groundwater pumping had minimal bearing on preventing overuse of groundwater sources (Negro and Porter, 2009; Daly, 1995). Since 1905, municipalities needed to be granted permits to pump groundwater for public water supply (Joshi, 2005). The next milestone was the *1972 New York Environmental Conservation Law*

(Chapter 43-B) that set standards to reduce over-pumping to prevent upwelling of brines to maintain water quality. In 1988 the *Great Lakes Water Conservation and Management Act* (NYS ECL § 15-1501 et seq.) was passed, imposing EIA requirements on public water supplies that withdrew large amounts of water from the GLB. It was not well after the *2005 GLSWRA* that volumetric limits to groundwater withdrawals were established when the *2012 Water Resources Law* (ECL Article 15-1501) was passed requiring a permit from the DEC for pumps taking over 100,000 gallons per day in order "to regulate the use of the State's water resources."

- *Illinois*

In Illinois, groundwater uses have for the most part proceeded without reasonable use limits, volumetric controls or policies restricting groundwater use in times of drought. Additionally, Illinois is one of two GLB states initially using the *Absolute Ownership Rule* in case law applied to resolve groundwater use conflicts, applying it well into the 1980s (Janasie, 2020). The *Edwards vs. Haegar* (180 III. 99) ruling in 1899 allowed for landowners to use groundwater without concern for impacts on neighboring users until the passage of the *1983 Water Use Act.* In this *Act*, the applicability of the *Reasonable Use Rule* to govern the State's groundwater withdrawals was confirmed. This was re-affirmed in the *Bridgman v. Sanitary District of Decatur* (164 III. App. 3d 287 4th Dist.) ruling which stated, "By using the terms 'natural wants' and 'artificial wants' in the definition of reasonable use…the legislature has adopted the same standards for groundwater withdrawals as that which applies to surface water withdrawals." Another step towards protecting GWS was the adoption of the *1987 Illinois Groundwater Protection Act* which enacted a series of technical programs and procedures to monitor statewide well levels. Though the 1980 Supreme Court Ruling (Wisconsin vs. Illinois, 449 U.S. 48) established the Chicago Diversion, precluding the state from any 2005 GLSWRA obligations, Illinois only permits bulk groundwater pumping for domestic uses per its *1996 Rules and Regulations for the Allocation of Water from Lake Michigan*.

– <u>*Ohio*</u>

As per court rulings dating from 1861, Ohio initially applied the *Absolute Ownership Rule* in regulating how much groundwater landowners could use, joining Illinois as the second state to do so in the GLB (Joshi, 2005). Courts provided no legal remedy for complaints of excessive use until a 1984 Ohio Supreme Court decision in *Cline vs. American Aggregates Corporation* which adopted the *Reasonable Use Rule* in its ruling, placing a duty on landowners to make a sensible use of groundwater to avoid harm to the groundwater rights of nearby landowners. The next significant step to safeguarding GWS was the 2003 amendment to the *Groundwater Rules and Regulations* (Ohio Administrative Code Reg. 3745-34) which required groundwater use permits to withdraw over 100,000 gallons per day, the same volumetric limit set for surface water.

3.4. Discussion

Consecutive binational agreements, multilevel statutes and court decisions leading up to the present-day GWS governance framework have certainly contained features beneficial to maintaining groundwater quantities. The establishment of the *1956 Great Lakes Basin Compact* was a milestone initiating successive agreements that deepened the whole of basin approach that has come to characterize current GLB water quantity governance. In developing this integrated approach, binational agreements have encouraged scientific inquiry and water use data sharing (Hammer, 2018). This has also been a long-standing feature of the Basin's federal governments, with the early establishment of the USGS and CGS, and its long-term technical support to the states/provinces in aquifer mapping and monitoring GWS levels. Moreover, the states/provinces have fairly consistently required GWS level data collection, and in some cases, have long required pumping rate reporting such as Ontario, Minnesota and Wisconsin.

Setting requirements for tracking GWS levels and aquifer extents are important aspects of sustainable GWS governance (Rivera, 2015), particularly as they are foundational to informing appropriate volumetric and temporal/seasonal limits to groundwater use which is needed in drought-prone and/or groundwater-dependent GLB communities (Dellapenna, 2014). However, throughout the 112 years since the *1909 Boundary Waters Treaty*, our findings suggest that multilevel governments have inadequately kept pace with advances in hydrogeological science in devising policies and standards for groundwater use and conservation over the years.

Focusing first on groundwater use, successive, multilevel statutes have generally failed to devise specific volumetric use limits corresponding to groundwater's relative scarcity and lower recharge rates. Policies typically have not contained evidence of appreciation that surface water can be recharged at an exponentially faster rate than groundwater; and that there is roughly six times more surface water than groundwater stored in the Basin (Coon and Sheets, 2006). Instead, the same, high volumetric water use thresholds have triggered governmental oversight, seeming to be better suited to surface water's greater availability and quicker recharge rates (Gosman, 2011). With multilevel governments limiting their GWS regulations to bulk groundwater use, another significant governance blind spot has involved the paucity of regulation of smaller quantities of groundwater uses. Done through allowing exports of groundwater from the Basin in containers 20 litres or less, as well as through the lack of regulation of water use quantities less than bulk water definitions, there has been a lack of consideration of cumulative impacts that smaller groundwater takings can have on aquifer storage over time.

On conservation, multilevel policies and decision-making standards have had a mixed record on enacting specific, science-based measures to conserve GWS. Positive developments over the years were the introduction of EIA requirements in PTTW decision-making standards beginning in the 1980s from some states/province, as well as some jurisdictions, such as Wisconsin, that protected waters needed for aquifer recharge. Over the study period, some states/province also introduced judicious water use policies for application during droughts, with Pennsylvania and Ontario being the only jurisdictions that made this mandatory through establishment of laws. Beyond this, most multilevel governments have provided little economic incentives or guidance on water use conservation measures to lengthen aquifer life. Moreover, there is little evidence to suggest that they considered quantitative evaluation of the trade-offs between future and current groundwater withdrawals that would be required for dealing with growing groundwater insecurity (National Research Council, 2007).

A good example of this is the historically low fees for municipal water supply and state/provincial well permits and PTTWs. As these fees have generally not been differentiated from the pricing structure for surface water, multilevel governments have provided little economic incentives for reducing groundwater use over the years. Past court rulings also provide more clarity on why most multilevel governments have unclear or non-existent GWS conservation measures based on aquifers' physical-environmental limits (National Research Council, 2007). Rulings resolving groundwater use disputes seem to have been rather focused on ensuring equitable groundwater rights of landowners rather than preserving aquifer storage (Bishop, 2006). Rather, courts have generally ruled in favor of those with the deepest wells and highest-capacity pumps such as in the Bralts and Leighty (no date) Michigan court ruling that "if a neighbor complains that your irrigation pumping is causing their well to go dry, a prudent response would be to offer to deepen their well and consider it an irrigation expense." These trends have led to an overall 3 percent increase in groundwater consumption concentrated in high-use hotspots across the Basin, while surface water consumption decreased within the study period (Pentland and Mayer, 2015).

Historical tracing points to 19th-century court decisions as providing the original legal principles that account for these governance gaps. The oldest of these is the *Absolute Ownership Rule*. Court deliberations in the 1843 Chasemore v. Richards ruling (1843-60 All E.R. 77, 81-82 H.L. 1859), sheds light on the state of hydrogeological science of the time that supported the creation of this legal concept. The court ruled that it could not limit the use of "…*water percolating through underground strata, which has no certain course and no defined limit, but oozes through the soil in every direction in which the rain penetrates*."

This legal point of view appears to have carried through in devising the *Underground Stream Doctrine/Reasonable Use Rule* by early North American governments. Remaining largely unchanged in the intervening years leading to the present-day GWS governance framework, they have innately skewed the legal understanding of groundwater flow systems as surface water tributaries. These principles clearly lack consideration of sustainable aquifer yield requirements, and have not kept pace with advances in science that increasingly recognized groundwaters as quantifiable resources supporting vital environmental functions and economically valuable human uses. As such, multilevel statutes and court decisions have been overwhelmingly oriented towards protecting surface water quantity, leading to a contemporary governance framework that is largely devoid of groundwater-science based guidelines for conserving GWS. These features appear to be especially pronounced in GLB states that have more history applying the *Absolute Ownership Rule* in court rulings to resolve GWS complaints such as Ohio and Illinois. Herein, there is a longer history of courts and statutes allowing landowners to pump groundwater without concern for environmental flows and future availability.

3.5. Conclusions

Historical GWS governance gaps have persisted not due to a lack of competence or understanding of hydrological science. This is demonstrated with multilevel governments having laws protecting groundwater quality since the 1970s that explicitly considered geophysical and other environmental parameters (Hodge, 1989). Kickstarted with major environmental disasters such as the Love Canal catastrophe that leached hazardous chemicals into underlying groundwaters in the Niagara escarpment, to widespread eutrophication of Lake Erie, general awareness of GLB water quality crises shifted public opinion leading to sweeping policy changes (GLSAB, 2018).

Path dependency—the phenomenon of governments starting down a particular track, making the costs of reversal or change extremely high to overcome—may be the likely rationale for GWS policy weaknesses persisting well into the present-day governance framework (Cerna, 2013) and inexorably contributing to growing water insecurity in drought-prone and/or groundwater-intensive locales. Policies are inherently challenging to reform (Pierson, 2000), even when suboptimal to address problems (Greener, 2002), and policy-makers typically wait for a critical juncture or exceptional opportunities to enact policy reform (Capoccia and Kelemen, 2007). Moreover, Hansen (2002) contends that "path dependence is established only when it can be shown that policy change was considered and rejected for reasons that cannot be explained without reference to the structure of costs and incentives created by the original policy choice."

Successive GLB governments have had little inducements to amend GWS governance as growing groundwater insecurities have been largely localized and location-specific problems

(Morris, Mohapatra and Mitchell, 2008). GLB residents have generally had low water risk literacy, lulled into the “myth of water abundance,” relatively unaware of risks posed by droughts and rising uses (Watershed Council, 2020; Kane, 2017). With growing groundwater vulnerabilities not yet garnering widespread public attention, or becoming a Basin-scale problem, there has not been sufficient public pressure or sufficiently significant inflection points demanding policy change. Also, as surface water has had a longer established track record of laws and jurisprudence to regulate water use and conservation, over the years it has been easier for multilevel governments and courts to continue to apply the same policies and decision-making standards for groundwater, rather than devise novel, groundwater-specific policies (Eckstein and Hardberger, 2017).

Projected increases in climate and human pressures will continue to undermine groundwater security in a “do nothing” policy scenario. Climate change will increase precipitation in the Great Lakes region. However, its pattern will be progressively altered, concentrating more precipitation within winter months when the ground is frozen, and infiltration is reduced. In these conditions, aquifer recharge is expected to decrease by up to 20 percent (Hall and Stunz, 2008). Currently, 10 percent of the US population and 40 percent of the Canadian population reside within the GLB (Chaloux and Paquin, 2013), with some of the fastest growth in inland peri-urban communities (GLC, 2016). For many communities, groundwater is often the sole source of public water supply: e.g., roughly half of Michigan residents and a third of Ohio residents rely on GLB groundwater for public water supply (Wilson, 2018). Industry is increasingly attracted to the Basin drawn by clean waters and cheap water prices (Bruneau, Dupont and Renzetti, 2013). These trends have contributed a thirty-fold increase in regional groundwater withdrawal, currently estimated at 160,000 litres/day (GLC, 2016), leading to groundwater over pumping concentrated at population growth and industrialized hotspots.

The above provides impetus for real reforms to ensure continued and equitable access to groundwater-dependent and/or drought-prone communities. To contend with these rising GWS threats, sustainable aquifer yield theory and empirical evidence argue strongly in favor of reforms of policies and standards regulating use and conservation. As demonstrated with the improvements made with water quality governance due to public pressure, inflection points can make fundamental governance reforms possible (Cerna, 2013). As such, our first recommendation is to raise awareness of the true availability and vulnerability of GWS in the Basin. As a water-rich region, these location-specific vulnerabilities are often overlooked, and only gain widespread attention when a crisis is reached (Annin, 2018). Raising awareness on the increasing cases and socio-environmental drivers of GWS vulnerabilities across the Basin is therefore key.

Secondly, we urge for groundwater use governance to keep pace with scientific findings of the twenty-first century. It is clear that current GWS governance remains based on legal concepts based on 19th-century science that are currently obsolete given advances in scientific understanding of GLB hydrogeology. Considering the growing recognition of groundwater's inimitable socio-environmental functions, modernization of legal principles and customary jurisprudence are due. To do this, multilevel governments and courts would need to make a definitive pronouncement regarding how the *Reasonable Use Rule* would be applied. Abandoning the *Underground Stream Doctrine*, determination of reasonable groundwater uses should be contextualized by sustainable aquifer yield requirements. To be mainstreamed as far as feasible across multilevel governments, this contemplates (i) specification of volumetric thresholds for reasonable groundwater uses in legal definitions; (ii) adding a temporal dimension to determining reasonable use by lowering use rates during times of drought and considering the cumulative impacts of smaller capacity wells over time (Water Systems Council, 2016); and (iii) differentiation of bulk water definitions for groundwater and surface water, with lower volumes set for the former given its relative scarcity and differing environmental safeguards.

Restricting what is now considered 'reasonable uses' of groundwater will require expansion of the *Public Trust Doctrine* (Eckstein and Hardberger, 2017). Originating from 6th century Roman civil law or "Institutes of Justinian," it obliges governments to protect in perpetuity "things common to mankind—the air, running water, the sea, and consequently the shores of the sea." Adopted in the constitutions of newly formed North American governments, its interpretation originally protected surface water and excluded groundwater (Kilbert, Merkle and Miller, 2019). However, applying public trust principles to govern groundwater use has been rejected in the past due to fears over violating private property rights (Abrams, 2012). A 1983 California Supreme Court ruling (*National Audubon Society v. Superior Court* 33 Cal.3d 419) provides a practical example for addressing this issue through sharing of public trust responsibilities with private landowners. To resolve a complaint by the National Audubon Society on the lowering Lake Meno's water level due to long-term pumping, the Court ruled that the public trust must be balanced between the Los Angeles Department of Water and Power and land proprietors. In so doing, it rationalized prior appropriation groundwater rights of landowners with the public lands and trust responsibilities of the government for conserving groundwater.

Our third recommendation is to incentivize groundwater use efficiency. The structure of costs created by past GWS governance policies has resulted in groundwater being cheap and freely available for well owners; and insufficiently covering the cost of extraction and distribution of municipal water supply (CEC, 2017). These features have been embedded in the business models of industries attracted to the region (Kotkin, Schill and Streeter, 2013). While most GLB states/province have had voluntary guidelines for water use efficiency, mandatory standards and/or economic incentives should be considered to curtain groundwater overuse. Such incentives can include rebates for installation of efficient plumbing, promotion of judicious irrigation methods and removing reducing block rates in municipal water supply tariff structures. Economic disincentives may also be considered, as illustrated in Ontario, which since the 1990s has set higher PTTW pricing for withdrawing bulk groundwater than surface water; and progressively increases costs for PTTWs for higher groundwater volumes.

Looking back at the century-old arc of water resource governance in the GLB, despite the surprising prominence of surface water policies being applied to govern groundwater use, there has also been a tradition of collaboration and cooperation. The region's multilevel governments have established enduring institutions and, more recently taken steps to enshrine transboundary water use policies into federal and state/provincial law, suggesting growing political will to have stronger water resource safeguards. Multilevel institutions have also a long tradition of funding and conducting important scientific studies on the current state of the Basin's groundwater resources which is needed for science-based governance reforms (GLSAB, 2018). With these ingredients and this historical trajectory, there can be some confidence in the GLB continuing its governance evolution towards better sustaining all water resources, rising to the challenges of growing climate and human-use stressors on vulnerable aquifers.

3.6. Acknowledgements

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4. Chapter 4

Weekes, K. and Krantzberg, G. (Submitted for Publication). "What Can We Learn About Improving Multilevel Groundwater Quantity Governance in the Laurentian Great Lakes Basin from the City of Guelph, Canada?" *Environmental Science and Policy*.

ABSTRACT

Amongst the world's largest freshwater stores, persistent groundwater storage (GWS) decline is increasingly reported in groundwater-dependent and/or drought-prone locales of the Laurentian Great Lakes Basin (GLB). Although governance lies at the heart of the capacity of water based social-ecological systems such as the GLB to address mounting GWS stressors, the usual governance response has been to increase surface water use. As this option is not always available further inland nor is it feasible with growing pressures, we draw lessons from a case study of the City of Guelph, Ontario—a drought-prone, groundwater-dependent GLB municipality that has managed to maintain its GWS. To investigate the degree to which this may be attributable to its GWS governance approach, we apply statistical analysis techniques to determine the governance and GWS relationship, comparing results with a GWS-climate correlation. Showing a stronger link between governance and long-term GWS maintenance, governance features that differentiate the City from most of the Basin's groundwater insecure locales include strong science-policy alignment of multilevel policies impacting GWS, prioritization of groundwater use efficiency, and temporal limits to groundwater use. Key to the success in maintaining GWS is the inclusion of municipal institutions in policy and decision-making, allowing for adaptive governance informed by local societal needs and physical-environmental limits of aquifers. With these lessons instructive to other communities, we urge GWS governance reform to avoid further proliferation of groundwater insecurity in a future expected to be marked by rising climate and human pressures.

4.1. Introduction

Rising population across the eight (8) US states and the province of Ontario that are within the hydrological extent the Laurentian Great Lakes Basin (GLB; *Figure 6*) has caused regional groundwater withdrawal to increase thirty-fold over the past 20 years (Howard and Gerber, 2018), now averaging 160,000 litres/day (Wilson, 2018). Despite being the globe's largest freshwater store, with 16 percent stored in the form of groundwater (Coon and Sheets, 2006), as rising groundwater use is not uniform, persistent groundwater storage (GWS) decline is an emerging issue at the GLB's sub-watershed scale. To illustrate, with intense groundwater use concentrated in peri-urban centers, 30 percent of Ohio residents and 50 percent of Michigan residents source water from GLB aquifers (Wilson, 2018). Further inland municipalities such as the Tri-City area —Kitchener, Waterloo and Cambridge—in Ontario rely almost entirely on GLB groundwater (Frind and Middleton, 2014).

Figure 6: States and Provinces within the Laurentian Great Lakes Basin Boundary (*Source: NOAA, 2004*)

At the same time, climate change is actively changing precipitation patterns, progressively reducing groundwater recharge (Minallah and Steiner, 2021). As 1 percent of the GLB's groundwater resources are renewed annually, (Xu *et al.*, 2020), growing groundwater uses coupled with impacts of climate raise the spectre of groundwater insecurities occurring across these situational contexts.

In social-ecological systems (SES) such as the GLB, governance lies at the heart of its capacity to maintain GWS considering the complex bio-geo-physical units and associated actors that use and impact aquifers. Governance provides policies and decision-making standards guiding management and societal actions affecting the resource (Megdal *et al.*, 2014). Policies and standards controlling groundwater use—i.e., withdrawals, allocations and diversions—have the most impact on sustaining GWS (Dellapenna, 2014). Thus, rising GWS risks highlight disconnects between groundwater use policies and standards vis-à-vis measures addressing socio-environmental stressors in the usual governance response to address groundwater insecurity.

As federalized transboundary states, decisions and policies devised at the binational to state-provincial levels typically address GWS vulnerabilities by supplementing demand with nearby surface water resources. For example, a 1980 US Supreme Court decree authorizing new allocations of Lake Michigan water was done to address GWS decline in aquifers in the Chicago–Milwaukee metropolitan area. This resulted in groundwater withdrawals dropping from 1.2 billion litres/day in 1980 to .75 billion litres/day by 1994 and some recovery of groundwater levels (USGS, 2005; Granneman *et al.*, 2000). A similar policy was implemented in Green Bay, Wisconsin and Toledo, Ohio and more recently in Detroit and Grand Rapids, Michigan (USGS communications on December 3rd, 2019). Moreover, this situation prompted the recent successful application for an out-of-Basin diversion of Lake Michigan water to the straddling GLB municipality of Waukesha, Wisconsin. As the municipality's drinking water supply was contaminated with radium due to long-term over pumping (Choi *et al.*, 2012), the Great Lakes

Council (the main binational body regulating bulk GLB water resource uses) granted their request in June 2016 (GLSLCI, 2018).

The governance option of switching to surface water resources is out of reach in many inland GLB communities given the often-insurmountable expense of piping in surface water supplies from bodies further afield. To illustrate, plans to build a pipeline to supplement the groundwater-dependent Tri-City area, Ontario have been around since the 1960s as public water systems have increasingly struggled to supply sufficient water to growing residents. A constant challenge has been high costs, which at its last estimate was CAD $1.2 billion (Frind and Middleton, 2014).

Despite growing groundwater supply risks being at the sub-watershed scale and directly affecting municipal residents, municipal governments and watershed management organizations (WMOs) are not usually involved groundwater use governance (Cohen, 2009). With the exception of municipalities within Ontario, the Basin's 263 municipal jurisdictions' role has been largely limited to monitoring groundwater table levels and devising local land use plans useful for protecting aquifer recharge (Kreutzwiser, Durley and Priddle, 2013). Ontario's municipalities are legally required to be involved in policy and decision-making on groundwater use. One of these, the City of Guelph, is a wholly groundwater-dependent GLB municipality that has maintained GWS despite growing populations and being located in a drought-prone watershed.

Considering the region's uncertain climate future, increased population and attendant demands on groundwater, as well as data gaps on the full extent of groundwater insecurity, GLB governments will need to more proactively and directly address human and environmental drivers of GWS decline to maintain the resource in vulnerable and potentially vulnerable locations (Bakker and Cook, 2011). Towards this goal, in this paper, we draw lessons from the multilevel

GWS governance approach applied in the City of Guelph.We examine the reasons the City has had different GWS outcomes as compared to other GLB municipalities facing similar human and climate stressors on its aquifers. Lessons learned can be useful to improve governance in GLB locales vulnerable to droughts and groundwater shortages.

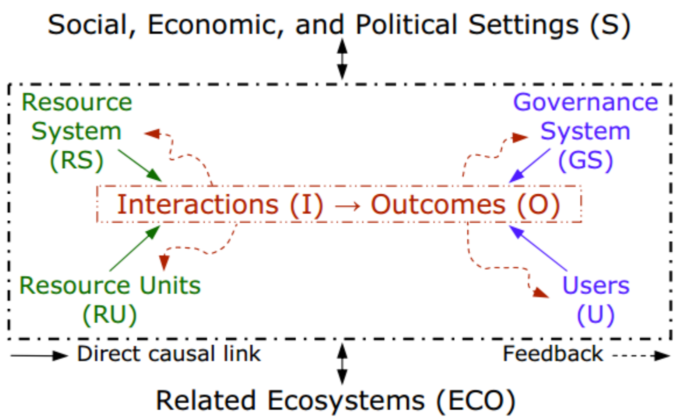
4.2. Methodology

4.2.1. Analytical approach

The governance-aquifer interactions and feedbacks that impact GWS sustainability in in the City of Guelph are complex. As such, one singular analytical discipline will be insufficient to properly examine the multilevel GWS governance approach applied in the City that has seen long-term GWS stability outcomes. To tackle these complexities in SESs, "critical multiplism" (Ostrom *et al.*, 2002) involving the use of theories, methods and perspectives from differing disciplines, is needed to evaluate the governance features that impact GWS.

To accommodate this analytical approach, we design the case study using the SES Framework (Ostrom, Janssen and Anderies, 2007; *Figure 7*) as its components allow for (i) clear ways of linking and describing variables and interactions from societal and environmental systems; (ii) application of multidisciplinary methods to describe causal relationships (i.e., interactions and outcomes) between social-ecological variables that impact resource sustainability; and (iii) analysis of transient aspects of interactions through time and space (McGinnis and Ostrom, 2014).

Figure 7: Basic Structure of the SES Framework (*Source: Ostrom, Janssen and Anderies, 2007*)



At its core, this study evaluates the degree to which the City's unique governance approach can explain its successes in maintaining GWS, as opposed to other socio-environmental factors. To do this, the study will need to establish the causal relationship between the City's governance approach and GWS outcomes. Whilst the SES framework "provides the basic vocabulary of concepts and terms" useful to construct causal explanations, it is insufficient to establish causation as this requires statistical methods (McGinnis and Ostrom, 2014). We evaluate the strength of the causal relationship between governance and GWS using statistical correlative and hydrogeological science methods. We then apply political science theories and methods to interpret governance features that may or may not have had influence on positive GWS outcomes.

Results of these multidisciplinary analyses are interpreted from the perspective laid out in UNESCO's sustainable management guidelines for non-renewable groundwater resources. Originally developed by Foster and Loucks (2006), these guidelines have been applied and modified in seminal research over the years (Foster and Ait-Kadi, 2012; Majidipour *et al.*, 2021). We apply this perspective normatively, where long-term GWS decline indicates that governance is ill-suited to the physical-environmental sustainability needs to maintain GWS. When governance effectuates actions resulting in increased and/or long-term stability of GWS and optimal economic development, it is considered effective.

Sustainable aquifer yield considerations are used as evaluative indicators to decipher the specific governance features that may or may not have had impact on maintaining GWS. Within sustainable aquifer yield theory (Lin and Lin, 2019; Freeze and Cherry, 1979), aquifers are considered to be water limited, with tradeoffs between shifting precipitation inputs and pumping, that is controlled by groundwater use governance, to maintain GWS (Massuel *et al.*, 2013). As such, governance features effective in maintaining GWS governance can be deduced by the extent to which they reflect: (i) GWS being inherently limited by unique geophysical parameters of aquifers; (ii) climate factors controlling natural aquifer recharge; (iii) measures to maintain environmental flows of aquifers; and (iv) whether allowed human uses sufficiently maintain GWS and environmental flows while avoiding unwanted socio-economic outcomes.

4.2.2. Data and methods

The case study was done over three distinct analytical phases: (i) characterizing the social and ecological components that impact GWS in aquifers supplying the City of Guelph; (ii) evaluating the extent to which the maintenance of GWS (SES "Outcomes") in aquifers supplying the City can be attributed to governance rather than other environmental factors; and (iii) interpretation of results (SES "Interactions"), synthesis and GWS governance reform recommendations to conclude.

- *Characterizing the City of Guelph's SES relevant to maintaining GWS*

Using the basic components of the SES Framework, we first described the (i) "Resource Units" and "Resource System" characterizing the geophysical parameters of the City's aquifers and climatic drivers that inherently limit GWS; and (ii) "Users" comprising all human and ecological groundwater users within the City and the quantities used. Data was sourced from publications and official government reports from publicly accessible repositories. Data was also sourced from, and analysis validated by, expert interviews with personnel from Water Services and Environmental Services Department of the City of Guelph and Grand River Conservation Authority (GRCA).

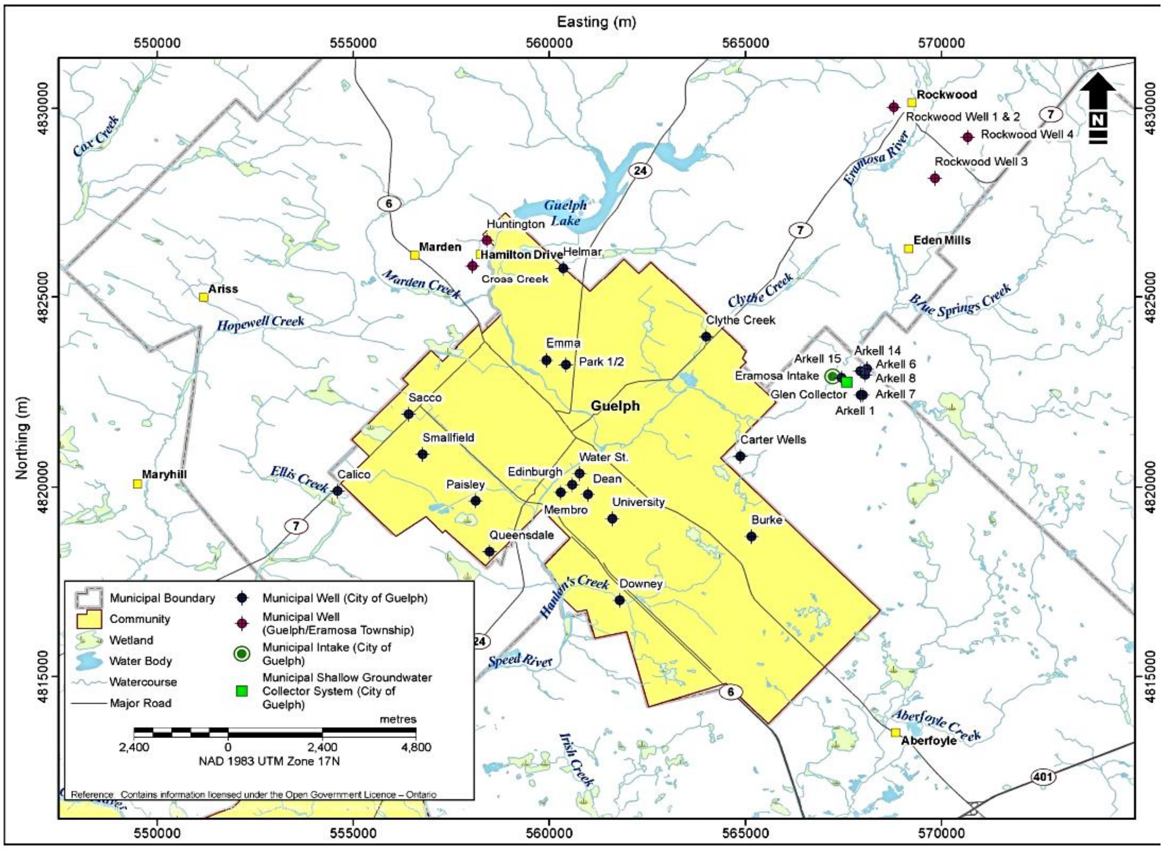
- *Evaluating the extent to which the maintenance of GWS in aquifers supplying the City can be attributed to governance rather than other environmental factors*

We used proxies for this analysis, interpreting historical groundwater table levels as representative of long-term GWS trends as it "provides summary information about the present state and trends in groundwater systems and helps to analyze the extent of natural processes and human impacts on groundwater system in space and time" (Vrba and Lipponen, 2007). Per North American institutional history, the most important of policies and standards controlling groundwater use are those that set pumping rates (Kreutzwiser, Durly and Priddle, 2013). As such, pumping rates of high-capacity wells were considered sufficiently representative of governance as large quantity withdrawals of the City's aquifers that affect GWS are set by multilevel policies, and require approval per standards set in Ontario's Permit to Take Water (PTTW) program. Pumping is also subject to stoppages or other reductions per laws governing groundwater uses during droughts.

To represent climate factors impacting GWS, we determined long-term precipitation data to be suitable a proxy. This is because, aside from geophysical characteristics of aquifers affecting groundwater transmissivity, rainfall is the only other environmental factor that can control recharge and the only parameter that can fluctuate over time (Massuel *et al.*, 2013).

The City of Guelph has 64 operational high-capacity wells with PTTWs, including 21 municipal drinking water supply wells and 41 non-municipal, private wells. There are also 125 functioning private, smaller-capacity wells within the City (GRCA, 2017).

Figure 8: Location of Permitted High-Capacity Wells in the City of Guelph (*Source: GRCA, 2017*)



Groundwater table level data was sourced from the 11,132 daily observations of hydraulic heads in the 21 high-capacity municipal wells located throughout the City (*Figure 8*) from 2002 to 2017. Hydraulic heads from these wells were considered sufficiently representative of long-term GWS trends as the City's high-capacity wells are hydraulically connected as they interfere with each other given that they mainly pump from the Gasport Formation (GRCA, 2018; GRCA, 2021). Pumping rates from private, smaller capacity wells are considered too small to have significant impacts on overall GWS (GRCA, 2018).

Proxy data representing GWS governance was sourced from daily pumping rate recordings from 2002–2017 from municipal wells released by the Water Services and Environmental Services Department. Daily precipitation representing climate factors that can have impact on GWS, were sourced from 12,383 daily observations from 2002–2017 from rain gauges in the Grand River Watershed within which the City lies. This data was sourced from GRCA's public database.

To decipher the degree to which long-term stability of GWS in the City's aquifers can be attributed to its unique governance approach, we compared correlations of (i) groundwater table levels to pumping rates with (ii) groundwater table levels to precipitation, from 2002-2017. Municipal wells are divided into quadrants for the City's management purposes, with the North East Quadrant containing four operational wells, the North West Quadrant three wells, the South East Quadrant nine wells and the South West Quadrant five wells (GRCA, 2021). As such, we conducted analyses for each quadrant and conducted a fifth analysis for all wells. Correlation analysis was done using Pearson's correlation coefficient described in *Formula 1* using STATA software.

[*Formula 1*]

$$r_{xy} = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left(n\sum x^2 - \left(\sum x\right)^2\right)\left(n\sum y^2 - \left(\sum y\right)^2\right)}}$$

Where: ***r*** is the measure of the strength of a relationship; ***x*** is the dependent variable (groundwater table levels); and ***y*** is the independent variable (either governance or precipitation). Results of Pearson's correlation coefficient vary from **−1** to **+1** where **–1** is the strongest possible dissociation; and **+1** is the strongest possible correlation with GWS outcomes.

To provide visual demonstration of the impacts of governance on long-term GWS trends in the City's aquifers, we also developed composite hydrographs. As they can smooth out seasonal weather effects on groundwater table trends, they show more clearly the overall, long-term impact of pumping and/or climate (USGS, 2018). We 'blended' groundwater table data calculating the median annual levels in sampled wells in each of the City's quadrants and then averaged their median levels in each year from 2002-2017. Groundwater table trends for each quadrant were graphically displayed on Microsoft Excel worksheets (see *Appendix II*) with each year of the study on the *X* Axis and averaged, annual median groundwater table levels on the *Y* axis.

- *Interpretation of results and synthesis.*

Results of the correlation analysis and composite hydrographs were interpreted considering hydraulic principles of water flow across different geological media (Freeze and Cherry 1979). Sustainable aquifer yield requirements were applied as evaluative indicators to interpret the GWS governance implications of statistical and hydrograph results. In so doing, we assessed the degree to which the SES 'Governance System', contained binational to municipal level policies and decision-making standards, considered physical-environmental limits of aquifers in regulating groundwater uses. Results were synthesized in the *Discussion*, and key lessons deduced in the *Conclusion* for improving GWS governance in vulnerable GLB locales.

4.3. Results

4.3.1. Users

- *Environmental Users*

Covering an area of 87.22 km^2, the City's ecoregion is diverse, with habitats relying on several groundwater-dependent environmental features. These include wetlands, environmentally sensitive areas and cold-water streams fed by groundwater fluxes. Groundwater fluxes are critical to maintain the headwaters of the Eramosa River, Blue Springs Creek, Clythe Creek, Hanlon Creek, Speed River, Irish Creek, Mill Creek and Hopewell Creek (Aquaresource, 2009b).

- *Human Users*

Corresponding to our 2002-2017 study period, in 2002, the City's resident population was 125,275 with a commuting working population of 66,730 (COG, 2014). Amongst the top seven growing Canadian cities, the City's residential population increased to 131,794 as at 2016 (Census Canada, 2019). During this period, per capita groundwater demand from the residential and commuting population increased from 42,595 litres/day in 2012 to 46,943 litres/day by 2018 (GRCA 2017). *Table 7* provides the 2017 profile of the City's high-capacity well owners, maximum pumping rates allowed in their PTTWs and average daily groundwater demand.

Table 7: Profile of Groundwater Users, Permitted Rates and Consumption in the City of Guelph (Source: *GRCA, 2017*)

Groundwater Using Sector	Maximum Permitted Rate (m^3/day)[1]	Consumption (m^3/day)[2]
Municipal Supply	132,600	47,681
Pits and Quarries	13,750	7,888
Golf Course Irrigation	4431	878
Other – Agriculture	3880	374
Aquaculture	3274	1783
Other – Industrial	1635	105
Bottled Water	1113	499
Other – Water Supply	1111	24
Heat Pumps	816	816
Brewing and Soft Drinks	553	0
Field and Pasture Crops	537	75
Groundwater	512	183
Other – Remediation	402	120
Other – Institutional	137	137
Cooler Water	110	53
TOTAL	**164,816**	**60,563**

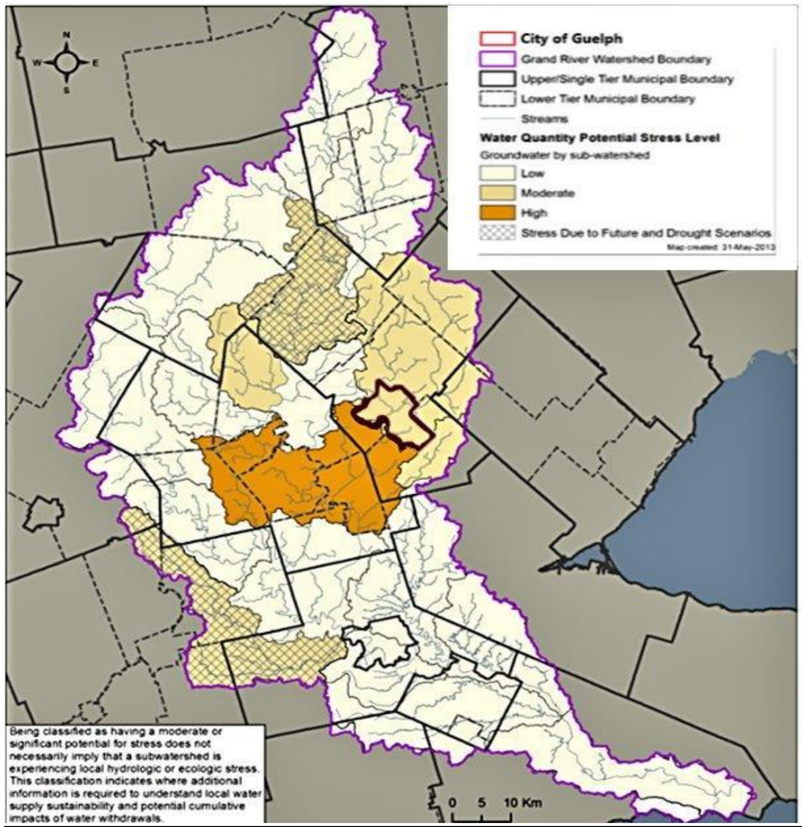
1 Permitted rates were effective as of 2013 and were valid within study period
2 Reported Rates to the OMEPPR

4.3.2. Resource system and resource units

During the study period, the total average daily groundwater demand of the all the City's human users (residential, industrial, agricultural and commercial) was 60.56 million liters /day (GRCA, 2017). Human use was well within the sustainable yield of the of the City's developed aquifers which is estimated at 83,836 m^3/day (COG, 2014). However, as the City of Guelph is completely reliant on groundwater (Frind and Middleton, 2014), rising groundwater demand is a stressor to the City's GWS, particularly during droughts and the summer agricultural growing period. This is because, except for irrigation that provides some return flow to aquifers, all groundwater use is consumptive as wastewater is not returned to source aquifers and is instead discharged into nearby rivers (Aquaresource, 2009a).

In terms of climate stressors, the City of Guelph is located in a region defined by the *2006 Clean Water Act* as having moderate groundwater stress (*Figure 9*). Changing climate has already reduced average annual precipitation by 0.2 mm from 1881 (Canadian Climate Data, 2020) and models project the watershed having over 45 days/year exceeding 30°C by 2080, with more frequent and severe droughts (Byun, Chiu and Hamlet, 2019).

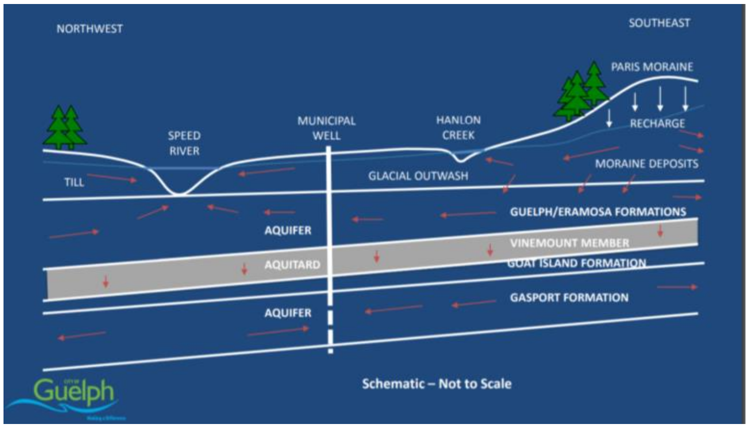
Figure 9: Location of the City of Guelph in the Grand River Watershed of the GLB (*Source: GRCA, 2018*)



With the exception of three of the nine wells within the City's South East Quadrant, all of the City's wells draw from the Gasport Formation, an Early Silurian sedimentary bedrock formation that is confined by the Vinemount Member regional aquitard (*Figure 10*), that together produce 75% of groundwater pumped by municipal wells (GRCA, 2021). The Gasport Formation is thick and has high hydraulic conductivity and transmissivity, allowing for lateral flow of large volumes of groundwater sufficient to meet human demands (Brunton, 2009). In the South East Quadrant, one well pumps the Guelph Formation (*Figure 10*), an unconfined sedimentary geological unit, that accounts for 5% of groundwater supplied by municipal wells (GRCA, 2021). Two wells pump from the Arkell Spring Grounds Glenn collector system, an artificial water recharge scheme that collects shallow groundwater from the overburden and the Gasport

Formation through a series of perforated pipes. To supplement recharge, from April to November the City also draws water from the Eramosa River. These wells account for 20% of groundwater pumped by municipal wells (GRCA, 2021).

Figure 10 Schematic of the Hydrostratigraphic Sequence of Groundwater Sources of the City of Guelph (Source: COG, 2019)



In terms of the cycling of water in the City's groundwater flow system, as the Gasport Formation is confined, vertical exchange of groundwater with the Guelph Formation is restricted as is water exchange with the nearby Speed and Eramosa rivers. Though subject to seasonal and climate variations, natural recharge of the Arkell overburden aquifer is safeguarded as the area is included in the 22 percent of spatial area of the City of Guelph that is fully protected for environmental purposes (GRCA, 2017).

4.3.3. Interactions

- *Relationship between Pumping Rates and Groundwater Levels in the City of Guelph*

The results of our comparative correlative analysis in *Table 8* show positive correlation between pumping and groundwater table levels, and little to no correlation between precipitation and groundwater table levels.

Table 8: Results of Correlation Analysis Comparing Strength of the Relationship Between GWS and Pumping vs. GWS and Precipitation

GROUNDWATER TABLE LEVELS OF WELLS IN EACH QUADRANT	RAINFALL	PUMPING
North West	-0.01	+ 0.32
South West	0	+ 0.40
North East	- 0.01	+ 0.44
South East	0	+ 0.31
CITY-WIDE	**-0.005**	**+ 0.3675**

Results of the composite hydrograph analysis (included in *Appendix II*) also suggest that changes in pumping rates have had more influence on groundwater table levels than changes in precipitation over the study period. There were significant fluctuations in groundwater table levels corresponding to changes in pumping rates, with groundwater table levels rebounding with stoppages or periods of low pumping. These outcomes likely occurred because, with the exception of three wells in the South East Quadrant, wells pump solely from the Gasport Formation that is confined by the Vinemount Member (GRCA, 2021) which causes precipitation to have negligible impact on its groundwater table levels. Moreover, in the South East Quadrant's composite hydrograph, the effects of precipitation on long-term groundwater table level trends are likely to have been obscured by the City's artificial recharge program in the two wells tapping the Arkell Spring Grounds Glenn collector system, or too small to have impact given that the well tapping the Guelph Formation accounts for only 5% of pumped municipal groundwater.

By the end of the study period, groundwater table levels in the composite hydrographs had an overall net increase and/or remained constant in all the City's quadrants except for the North West Quadrant where wells showed an overall decline in hydraulic head. The overall net decrease in groundwater table levels of wells in the North West Quadrant can be attributed to the dewatering of the Dolime Quarry which has already reduced groundwater levels from 290 to 288.4 masl as at 2018 (GRCA, 2018). The overall net increase and/or stability of groundwater table levels in the rest of wells likely occurred as although hydraulic heads temporarily draw down with pumping, if aquifers are not being over-pumped, groundwater table levels will eventually rebound to pre-pumping levels (Freeze and Cherry, 1979). The City's wells are pumped at rates well below the maximum allowed in PTTW's (per *Table 8*) and are subject to periodic pumping stoppages which allows for groundwater table rebound in the highly transmissive Gasport Formation.

4.4. Discussion

Results of the comparative correlative and composite hydrograph analysis suggest that GWS governance has been the main determinant of groundwater table levels in aquifers supplying the City of Guelph. The long-term stability of groundwater table levels indicates that GWS governance has been sustainable and well suited to the physical-environmental constraints of the City's aquifers despite the City's growing population and groundwater demand.

Governance features that are responsible for these outcomes are fundamentally linked to the City being within the jurisdiction of Ontario. Herein, there is a more robust framework of multilevel policies and decision-making standards (*Table 9*) addressing groundwater quantity than exists in most GLB municipalities (Weekes, Krantzberg and Vizeu, 2019; Weekes and Krantzberg, 2021).

Table 9: Policies and Decision-Making Standards Applied to Govern Groundwater Use and Conservation in the City of Guelph

BINATIONAL	1. *1909 Boundary Waters Treaty* 2. *1994 North American Free Trade Agreement* 3. *2005 Great Lakes- St. Lawrence Basin Sustainable Water Resources Agreement*

	4. 2012 Great Lakes Water Quality Agreement
FEDERAL	*5. 1867 Canadian Constitution Act* *6. 1985 Boundary Waters Treaty Act* *7. 1990 Fisheries Act*
PROVINCIAL	*8. 1990 Ontario Drainage Act* *9. 1993 Ontario Water Resources Act (particularly the PTTW program in Ontario Regulation 225/14)* *10. 2001 Municipal Act* *11. 2002 Ontario Low Water Response Act* *12. 2006 Clean Water Act (particularly its 2016 Technical Rules)* *13. Places to Grow Act 2005* *14. Niagara Escarpment Plan* *15. Greenbelt Protection Act* *16. Planning Act-Bill 51*
MUNICIPAL	*17. 1991 Water Bylaw* *18. 1995 Zoning Bylaw* *19. 2012 Official Plan Amendment 48* *20. 2014 Outside Water Use Bylaw-19714* *21. 2014 Water Supply Master Plan Update* *22. 2017 Official Land Use Plan* *23. Source Water Protection Plan* *24. Development Engineering Manual* *25. Grand River Source Protection Plan* *26. Lake Erie Source Protection Plan*

At its core, the relative robustness of Ontario’s GWS governance can be attributed to the *1867 Canadian Constitution* that confers provinces broad autonomy in water governance, unlike the GLB states whose role is bound within limits approved by the US Congress (Kreutzwiser, Durley and Priddle, 2013). Thus, Ontario has had more autonomy to set its own regulations impacting GWS and has opted to do so in a relatively science-based manner in consultation with municipalities and its system of Conservation Authorities (CAs), 35 of which exist within the GLB (Conservation Ontario, 2019). CA jurisdictions are based on watershed divides and are staffed by technical and municipal personnel. CAs carry out water stewardship, monitor ecosystem health, assess water quantity and quality and provide best-practice advice on the use and conservation of water resources.

In this manner, Ontario was able to incorporate stricter groundwater conservation safeguards than those set in the most recent binational agreements impacting GWS when it adopted its policy prescriptions into laws. The first is the *2005 Great Lakes- Saint Lawrence River Basin Sustainable Water Resources Agreement* (*2005 GLSWRA*), a set of GLB water use governance prescriptions aimed at safeguarding the quantity of “all waters” of the Basin. The *2005 GLSWRA* recommends identical policies to guide groundwater and surface water use, disregarding the differences in availability and natural recharge rates between the two resources, with there being five times more surface water than groundwater stored in the Basin (Coon and Sheets, 2006). With few exceptions, it recommends regional review by Great Lakes governors and premiers for ‘bulk water uses’ defined as any person withdrawing over 379,000 litres/day “in any 30-day period (including Consumptive Uses) from all sources” or to divert any amount of GLB water.

When Ontario adopted *2005 GLSWRA* policies in the *Ontario Water Resources Act* it set stricter volumetric limits for its definition of bulk water and additional GWS protections. It required a PTTW for taking over 50,000 litres/day in any 90-day period and differentiated requirements for groundwater PTTWs than those for surface water; the most significant requirements being an environmental impact assessment (EIA) on aquifers before granting groundwater PTTWs and adopting a graduated approach to PTTW fees, with groundwater fees being higher than those for surface water. PTTW fees range from none for taking water from low environmental impact sources (mainly GLB surface waters), to its highest fee of $3,000 CAD for groundwater requests in a high-use regions and/or for water bottling purposes (*Section 34*). In so doing, policies recognize the physical-environmental sustainability requisites of aquifers that differ from surface water. These features differentiate Ontario from many GLB states, as many do not satisfy the bulk water definitions and minimum water preservation measures prescribed in the *2005 GLSWRA*; have identical PTTW fees for surface and groundwater that are typically low; and omit EIAs (Mayer, Mubako and Ruddel, 2016; Megdal *et al.*, 2014).

Although primarily focused on safeguarding the quality of GLB waters, *Annex 8* of the *2012 Great Lakes Water Quality Agreement* (*2012 GLWQA*) is the second binational agreement affecting GWS for which Ontario opted to set stricter environmental protections in legislating its policy prescriptions. *Annex 8* includes principles promoting coordination of GW governance and science to "*…to restore and maintain the chemical, physical, and biological integrity of the Waters of the Great Lakes*.". Significantly, the *2012 GLWQA* contains provisions addressing groundwater quantity risks in order to maintain baseflow fluxes needed to maintain the integrity of surface water quality. Ontario adopted and improved on these policies in an amendment to its *2006 Clean Water Act* and *2002 Safe Drinking Water Act* imposing pumping limits to avoid uptake of brines, and lowering groundwater pumping during times of drought, thus reducing aquifer over-pumping risks.

The City's positive GWS outcomes can also be attributed to the relatively strong alignment of multilevel policies and decision-making standards with groundwater sustainability science. The positive GWS impacts of this governance approach is assured by effective collaboration across government levels. The Canadian federal government regards knowledge gaps on cumulative impacts of groundwater taking on GWS and groundwater-surface water interactions as impediments to good groundwater governance (Natural Resources Canada, 2013). As such, it launched the Groundwater Information Network (GIN) in 2002 to conduct groundwater quantity assessments. Also, the Canadian Geological Survey provides technical support and data resources.

At the provincial level, though Ontario's MECP is ultimately responsible for granting PTTWs, it consults with the City of Guelph and the CA of the watershed in which it lies, the GRCA, to decipher whether local aquifers can sustainably yield requested groundwater quantities (Conservation Ontario, 2019). Ontario also has a Provincial Groundwater Monitoring Network (PGMN) consisting of 489 wells that monitor GWS quantity and quality in real time. Complimenting the federal GIN, the PGMN is managed jointly by CAs and the MECP (Conservation Ontario, 2013). There are currently two PGMN wells close to the City, but their location is insufficient to monitor the City's GWS. However, the City has been filling this gap by improving their own monitoring well network (GRCA, 2017) while the PGMN and GIN expands.

Further evidence of the science-policy arrangements and strong multilevel government collaboration that account for positive GWS outcomes in the City's aquifers is the alignment of multilevel policies that set mandatory standards for controlling groundwater use during droughts. Absent from many other GLB jurisdictions (Weekes, Krantzberg and Vizeu, 2019), Ontario's *Low Water Response Directive* of the *2006 Clean Water Act* requires CAs to proactively identify municipalities vulnerable to groundwater overuse and extreme seasonal variations. Assessments have three tiers of complexity, depending on the severity of risks, and are based on a methodology prescribed by the Act's *Technical Rules*. Demonstrating consideration of the unique sustainability needs of aquifers, there are more stringent thresholds for assigning water stress levels to groundwater flow systems than for surface water systems (MOECC, 2017). In Tier One Assessments, watersheds can be classified as having low to significant groundwater stress based on the percentage of groundwater demand on the total renewable groundwater supply (*Table 10*).

Table 10: Thresholds for Assigning Groundwater Stress Levels in Municipal Groundwater Supply (*Source*: *2006 Clean Water Act*).

GWS STRESS LEVEL	MAXIMUM MONTHLY % OF DEMAND VS. RECHARGE	AVERAGE ANNUAL % OF DEMAND VS. RECHARGE
LOW	>50	>25
MODERATE	>25	>10
SIGNIFICANT	0-25	>10

Municipalities assessed as having moderate to significant levels of groundwater stress have their aquifers evaluated using progressively granular data inputs (population growth, development and climate change) for modelling and future scenario development. Source Water Protection plans are then developed by CAs with strategies to reduce or eliminate existing and future significant drinking water threats per rules in *Table 11*.

Table 11: Risk Management Measure Evaluation Process

WATER THREAT LEVEL	MANAGEMENT REQUIREMENTS
LEVEL 1 – MANDATORY	Approximate impacts of major groups of threats (e.g., municipal, private water takers)
LEVEL 2 – SECTORS	Approximate impacts of sectors within major groups of threats (e.g., municipal water takings from one municipality vs. another)
LEVEL 3 – LOCALLY RELEVANT	Approximate impacts of specific/individual/local takings and local recharge.

It was within this process that a Tier Two Assessment was completed for the Grand River Watershed in 2009, evaluating the City of Guelph as having Moderate groundwater stress (Aquaresource, 2009a). Consequently, a Tier Three Assessment evaluating sustainability of the City's drinking water systems to the year 2031 was completed in 2017 (GRCA, 2017). The development of the *Source Protection Plan* completed in 2018 allowed the City to proactively implement measures to protect existing groundwater supplies (GRCA, 2018).

Another important governance feature is Ontario's *2002 Low Water Response Act*. It was established to address drought induced water conflicts (Disch, Kay and Mortsch, 2012). Including three levels of low water conditions and responses (*Table 12*), in severe droughts water use is automatically prioritized for fire fighters, hospitals and residential (non-lawn irrigation) over other uses. The City of Guelph typically has Level 2 low flow status in summer months due to lowered precipitation, allowing for more judicious groundwater use.

Table 12: Low flow triggers and Governance Responses (*Source: 2002 Ontario Low Water Response Act*)

LOW WATER FLOW LEVEL	TRIGGER	RESPONSE
LEVEL 1	Stream flow < 70% of normal summer flow AND/OR Precipitation < 80% of the average	Voluntary reduction of water use by 10%
LEVEL 2	Stream flow < 50% of normal summer flow AND/OR Precipitation < 60% of the average	Voluntary reduction of water use by 20%
LEVEL 3	Stream flow < 30% of normal summer flow AND/OR Precipitation < 40% of the average	Mandatory Use restrictions imposed

By GLB state laws, municipalities are generally prohibited from making policies and decisions controlling groundwater use (Kreutzwiser, Durley and Priddle, 2013). As such, the GWS governance feature that most sets the City of Guelph apart from most GLB municipalities is its novel set of bylaws on groundwater use. Aligned with Ontario's *2006 Clean Water Act* and *2002 Low Water Response Act*, the City's *2014 Outside Water Use Bylaw 19714* is the most significant. It requires efficient outside water use corresponding to three levels of intensity of dry weather periods and has a system of ticketed fines complimented rigorous monitoring and surveillance to ensure compliance, the first Canadian City to do so (COG, 2019a).

Level Blue requires careful outside water use in normal watershed conditions, requiring alternate days for water uses outdoors and judicious general water use. Water wastage may be fined with a $250 CAD ticket. *Level Yellow* is triggered when there has been two weeks without precipitation or when there has been less than 80 percent of the historical average precipitation over three months. At this level, there is increased surveillance for compliance, breaches of which may result in a $350 CAD ticket or court summons. *Level Red* prohibits all non-essential outside water use and sets a fine of $550 CAD or court summons for non-compliance. It is triggered when precipitation is less than 60 percent of the historical average. These measures are complimented by the City's *1995 Zoning Bylaw* prohibiting development in key groundwater recharge areas.

The final governance feature linked to the City's ability to safeguard its GWS is the proactive approach of the municipal government to addressing socio-environmental stressors to aquifers. Following *2006 Clean Water Act* water risk assessment methods, the City assessed three main threats that can imperil GWS in the future: (1) artificial recharge requirements of the Arkell Spring Grounds collector system that sources water from the Eramosa River and confined Gasport Formation; (2) dewatering of the Dolime Quarry that reduced safe available drawdown at the Membro municipal well by 45 percent as at 2018; and (3) reduced recharge as future land development will likely cover an additional 5 percent of recharge zones (GRCA, 2018).

Though total groundwater pumped by all the City's PTTW holders is currently 36 percent of the total maximum volume permitted per the City's *Water Supply Master Plan,* and 72 percent of the sustainable yield of aquifers, the City is also proactively planning for future implications of groundwater demand and climate on groundwater resources. As the City's resident and worker population is projected to increase by 88,379 by 2038 (COG, 2019a), models in the City's *Tier Three Water Budget Study* predict that many wells will be unable to meet future needs in some scenarios due to expected increases in demand (GRCA, 2017). In drought scenarios, models forecast a minimum 10 percent reduction of groundwater discharge to streams if pumping is increased to meet future expected demand.

Cognizant of these vulnerabilities, the City proactively enhanced their *Source Water Protection Plan* (COG, 2019b). GWS risk response strategies include municipal well optimization through reallocation of pumping rates; improving water use efficiency particularly during droughts; assessing viability of alternative water sources; increasing monitoring of non-municipal pumping; and improving aquifer recharge rates via low-impact urban development. In addition, the City's *Development Engineering Manual* was updated to require upkeep of pre-construction recharge rates post-construction. These align with the *Water Conservation and Efficiency Strategy* that recommends reclaiming landscaping water, reducing municipal pumping rates, and reducing average groundwater demand to 9,150 m^3/day by 2038 (COG, 2014). Finally, the City plans to update its *1995 Zoning Bylaw* per the *2017 Official Land Use Plan* to address aquifer recharge protection in future land development to accommodate expected population increase by 2031.

4.5. Conclusions

Our case study of GWS governance in the City of Guelph highlights two main lessons to cope with growing GWS insecurity in drought prone and/or groundwater dependent contexts across the GLB. First, the City's experience underscores the need for proactive governance approaches that emphasize science-policy alignment, groundwater conservation and water use efficiency. In most GLB jurisdictions experiencing growing groundwater insecurity, the same prices, standards and use quantities are required for using water from both surface and aquifer sources, ignoring fundamental differences in their availability and recharge rates (Weekes, Krantzberg and Vizeu, 2019). As well, these jurisdictions largely do not have multilevel policies in place for controlling groundwater use corresponding to temporal changes in environmental conditions such as droughts (Weekes and Krantzberg, 2021). The City of Guelph’s proactive approach to instituting these measures enabled it to avoid undesirable GWS outcomes.

The second lesson to safeguard GWS in high-groundwater-stress GLB locales is the need for strong collaboration across multilevel governments that enables adaptive GWS governance. A commonality across GLB jurisdictions experiencing persistent GWS decline is that they ignore the key role that the municipal governments can play in sustainable GWS governance as regulations are set by policies and standards developed by higher orders of government. In some jurisdictions, such as Michigan, municipalities are even legally prohibited from enacting or enforcing local ordinances that regulate withdrawals from high-capacity wells (1978 Michigan Public Health Code - PA 368, MCL 333.1101 to 333.25211).

This GWS governance approach is problematic in high-groundwater-stress locales as, though higher orders of government are generally better funded and have greater technical capacities, they can be prone to inadequate consultation with local communities (Cosens and Gunderson, 2021). In the case of the GLB, even decisions and policies that appear to be informed by science, due to lacking consultation, may be ill matched to the variety of socio-ecological settings across the 263 municipalities, 186 watersheds and thousands of smaller communities. Thereby, monitoring of GWS levels, development of relevant policies, considerations for granting PTTWs, and temporal groundwater use limits affecting local aquifers are set by higher order governments, mainly at the provincial/state level. Consequently, there is inadequate adaptive capacity and institutional flexibility (Dellapenna, 2014) which translates to insufficient consideration of the physical-environmental GWS conservation needs of sub-watershed scale aquifers; and deficient balancing of community-specific needs.

The potential pitfalls of the top-down governance approach described above are best illustrated by the way in which the City of Guelph deals with the potential harmful impacts that PTTW's granted by the provincial government can have on local aquifers. The maximum permitted pumping rate of all PTTW holders exceeds the City's aquifers' sustainable yield by 80,980 m^3/day (COG, 2014), illustrating a lack of consideration of the physical-environmental limits of local aquifers. The potential impact on local aquifers of permit holders using the amount of water they are legally permitted to by the province is offset by the City's *Water Supply Master Plan*, *Source Water Protection Plan* and most importantly its *2014 Outside Water Use Bylaw 19714.* These plans set stricter groundwater conservation and use measures and prohibit groundwater use corresponding to three levels of intensity of dry weather periods. Moreover, unlike all other GLB municipalities, the City of Guelph is able to enforce these measures through ticketed fines cand rigorous monitoring to ensure compliance (COG, 2019a).

As groundwater insecurity is a location-specific GLB issue, excluding municipalities from GWS governance misses opportunities to leverage their jurisdictional scale, that are better matched with watershed scales and attuned to community needs (Hill *et al.*, 2008). The governance process of subsidiarity can foster these types of reforms (Cosens and Gunderson, 2021; Borgstrom *et al.*, 2006). Based on Integrated Water Resources Management where decentralized and consultative governance are core principles of resource sustainability, subsidiarity is the governance process by which shorter-term and smaller-scale duties are assigned to the lowest order of government with appropriate capacity, with the roles of higher orders of government limited to longer-term and larger-scale management (Stoa, 2016).

This is reinforced by the results of our case study that demonstrates that key to the City's ability to maintain its GWS, despite its drought-prone location and rising groundwater demand, has been due to significant groundwater use governance responsibilities being devolved through subsidiarity. Moreover, subsidiarity has also fostered strong partnerships and collaboration through the federal, provincial and municipal governments and CAs in scientific research and funding GWS monitoring, thereby enhancing the results of science-based policy development and decision-making.

Governance is the nucleus of the capacity of SESs to maintain water resilience to growing human and climate/environmental risks. Without policies adequately conveying the relative scarcity and risks to aquifers that are unique to each GLB watershed, GWS decline can be expected to continue (CEC, 2017). Rising climate and human pressures demand reform of the groundwater quantity governance approach generally applied across GLB jurisdictions to avoid further proliferation of localized GWS vulnerabilities. We urge greater democratization of the governance approach through subsidiarity, leveraging inherent advantages of municipalities to further the impact of science-based GWS governance outcomes that are grounded on the unique socio-spatio-temporal conditions that control GWS in local aquifers.

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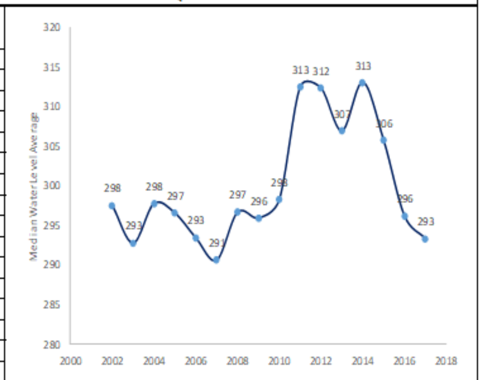
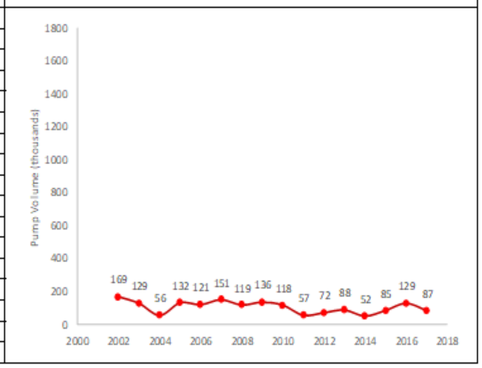
Appendix II. Long-Term Trend Analysis of Pumping and Groundwater Table Levels in Aquifers supplying the City of Guelph

Northwest Quadrant

Year	Median Water Level Average
2002	298
2003	293
2004	298
2005	297
2006	293
2007	291
2008	297
2009	296
2010	298
2011	313
2012	312
2013	307
2014	313
2015	306
2016	296
2017	293

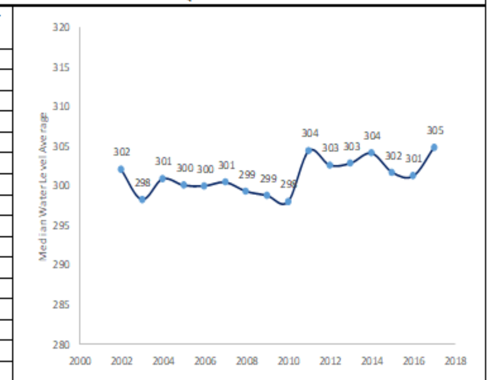


Year	Pump Volume
2002	169036
2003	128624
2004	55833
2005	132247
2006	121023
2007	150925
2008	119228
2009	136062
2010	118423
2011	56536
2012	71871
2013	88491
2014	51744
2015	85320
2016	129436
2017	86607

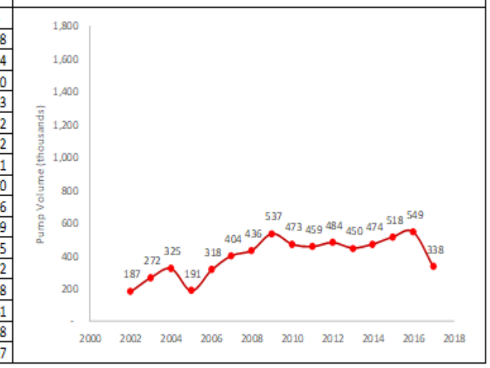


Northeast Quadrant

Year	Median Water Level Average
2002	302
2003	298
2004	301
2005	300
2006	300
2007	301
2008	299
2009	299
2010	298
2011	304
2012	303
2013	303
2014	304
2015	302
2016	301
2017	305

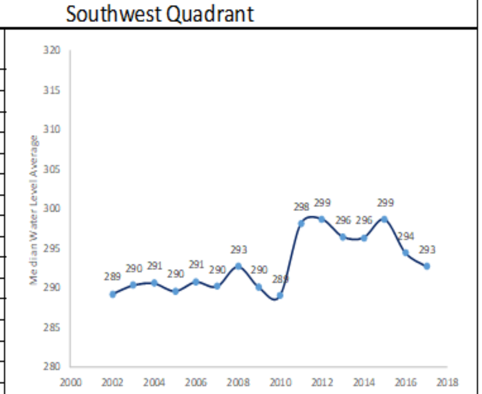


Year	Pump Volume
2002	186,908
2003	272,294
2004	325,020
2005	190,983
2006	317,822
2007	404,132
2008	436,211
2009	537,470
2010	473,456
2011	459,009
2012	483,735
2013	450,472
2014	473,958
2015	518,261
2016	548,688
2017	337,897

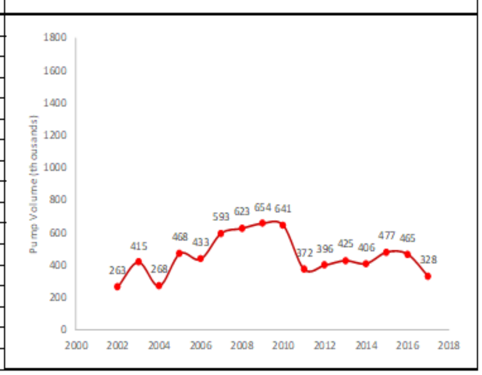


Southwest Quadrant

Year	Median Water Level Average
2002	289
2003	290
2004	291
2005	290
2006	291
2007	290
2008	293
2009	290
2010	289
2011	298
2012	299
2013	296
2014	296
2015	299
2016	294
2017	293

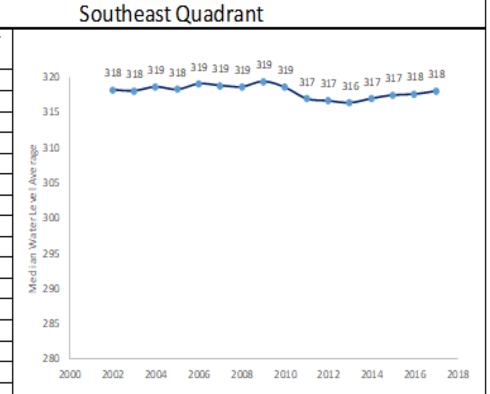


Year	Pump Volume
2002	262708
2003	415483
2004	267694
2005	467916
2006	433310
2007	592700
2008	622648
2009	653698
2010	641004
2011	371961
2012	395988
2013	424911
2014	406395
2015	477423
2016	464916
2017	328106

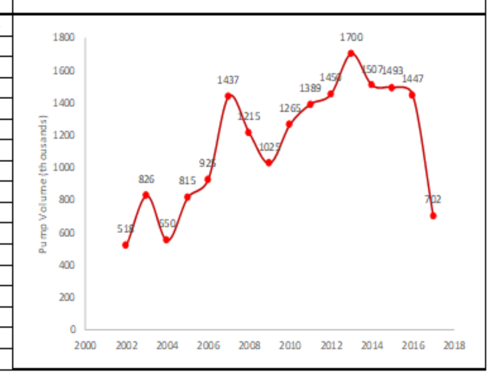


Southeast Quadrant

Year	Median Water Level Average
2002	318
2003	318
2004	319
2005	318
2006	319
2007	319
2008	319
2009	319
2010	319
2011	317
2012	317
2013	316
2014	317
2015	317
2016	318
2017	318



Year	Pump Volume
2002	517921
2003	826264
2004	550408
2005	815418
2006	925444
2007	1437169
2008	1214769
2009	1024928
2010	1265047
2011	1389064
2012	1449951
2013	1699658
2014	1506794
2015	1492909
2016	1447450
2017	701514



5. CHAPTER 5

CONCLUSION

This purpose of this dissertation's concluding chapter is to review the research findings presented separately in each chapter and assimilate them as a conceptual whole. In so doing, the research aim and objectives are first reviewed in section *5.1*. In section *5.2*, the main research findings from each chapter are summarized and connected to specific research objectives (*Chapters 2–4*). Section *5.3* outlines the original knowledge contributions made by this body of research and proposes preliminary recommendations for practice: a novel framework of good groundwater quantity governance principles designed to better maintain GWS in drought-prone and/or groundwater-dependent GLB communities. An explanation of overall research limits and recommended areas for future academic exploration are provided in section *5.4*. This chapter—and the dissertation as a whole—finishes with general research reflections in section *5.5.*

5.1. Aim and Research Objectives

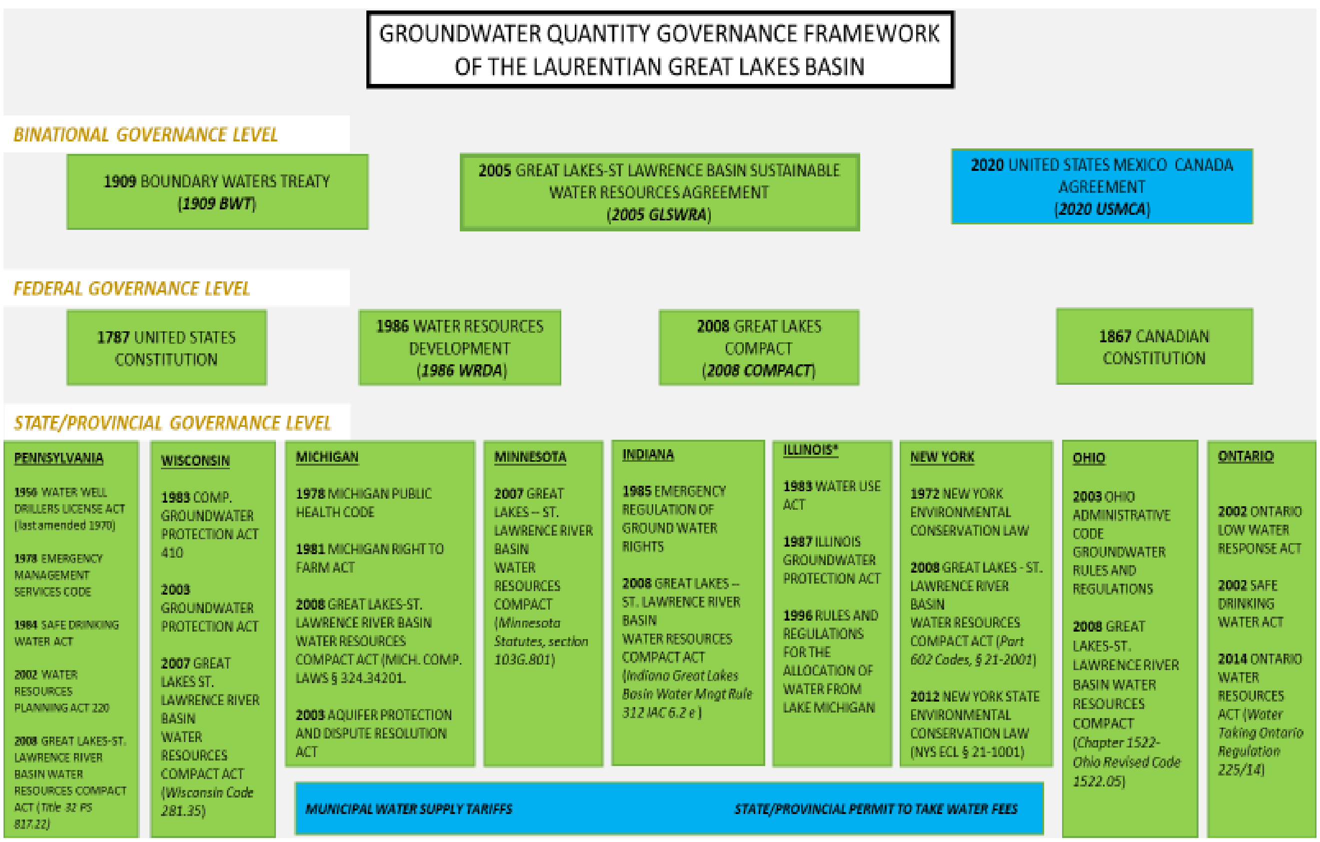
Researchers have long been concerned about the extent to which the governance framework applied to maintaining groundwater storage (GWS) in groundwater-dependent and/or drought-prone locales of the Basin may be fit for purpose (Hodge, 1989; Saunders, 2000; Kreutzwiser, Durley and Priddle, 2013; Dellapenna, 2014; Rivera, 2015; Kane, 2017; Sandhu *et al.*, 2020). This is especially in the context of persistent knowledge gaps on the true state of GWS levels and that groundwater security is not a widely reported issue throughout the Basin. These concerns have been based on rising reports of groundwater shortages and/or persistent GWS decline in high-groundwater-stress locations. Partially driven by steady increases in urban and peri-urban GLB populations, there has been a thirtyfold increase in groundwater abstraction in the past 20 years concentrated in localized, high-use hotspots (Howard and Gerber, 2018). Climate change has had a compounding effect, steadily intensifying seasonal variability (Persaud *et al.*, 2017); already, it is causing changes in precipitation patterns that will likely result in an up to 20 percent reduction in aquifer recharge in warming scenarios over 2.5°C in certain parts of the Basin (Lofgren, Hunter and Wilbarger, 2011).

In this empirical context, the dissertation aimed to identify features of the governance framework that may limit its effectiveness in safeguarding long-term GWS in groundwater-dependent and/or drought-prone communities and recommend prescriptions useful to policy-makers to improve GWS governance given rising human demand and climate pressures. On this basis, the overall research was framed as solving a problem within a social-ecological system (Ostrom *et al.*, 2002), carefully considering the complex and adaptive bio-geophysical units and associated actors that use and govern groundwater systems. In so doing, this dissertation explored the power dynamics of multilevel governance processes within a federalized, international basin setting, considering "power"—the ability to prohibit or make changes to achieve desirable outcomes (Sayer, 2012)—in the context of GWS governance as determining who has access to a resource, how it can be used and how much of it can be preserved for future use.

From this framing, this dissertation evaluated the degree to which emerging cases of GWS decline could be a panacea problem—a governance phenomenon in which blueprint policies are applied to solve complex natural resource problems via a top-down policy- and decision-making and enforcement approach, which often results in natural resource degradation (Falkenmark and Jägerskog, 2010). Thereby, GWS decline problems would occur if there is a lack of fit between policies and institutional practices vis-à-vis the physical-environmentally determined sustainability needs of groundwater flow systems and aquifers. As such, sustainable GWS governance was considered to imply the application of policies and decisions controlling groundwater use that also address socio-environmental GWS stressors.

The GWS governance framework (*Figure 11*) was conceptualized as encompassing binational to municipal-level policies and decision-making standards in common law, treaties, statutes and regulations that impact the long-term availability of GWS in high-stress locales. Per *Figure 11*, policies and standards were classified in two groups: (i) those directly controlling groundwater use: allocation, conservation and withdrawals; and (ii) those creating the economic conditions and incentives under which groundwater use decisions are made (Kemper, 2007; Sandhu *et al.*, 2020).

Figure 11: GWS Governance Framework of the Laurentian Great Lakes Basin (*Source: author's compilation*)



Key	
Groundwater Use Policy Tools	(green)
Economic Groundwater Policy Tools	(blue)

Over the course of this dissertation, four research objectives (ROs) were pursued to:

I. Identify features of critical policies, governance processes and roles of key institutions and stakeholders between and across binational to municipal government levels in the US and Canadian jurisdictions of the Basin that can lead to GWS decline in aquifers supplying high-stress locales;

II. Develop a baseline of empirical evidence of GWS outcomes that have resulted from binational and multilevel power dynamics, with an assembly of reported cases of persistent GWS decline in the GLB;

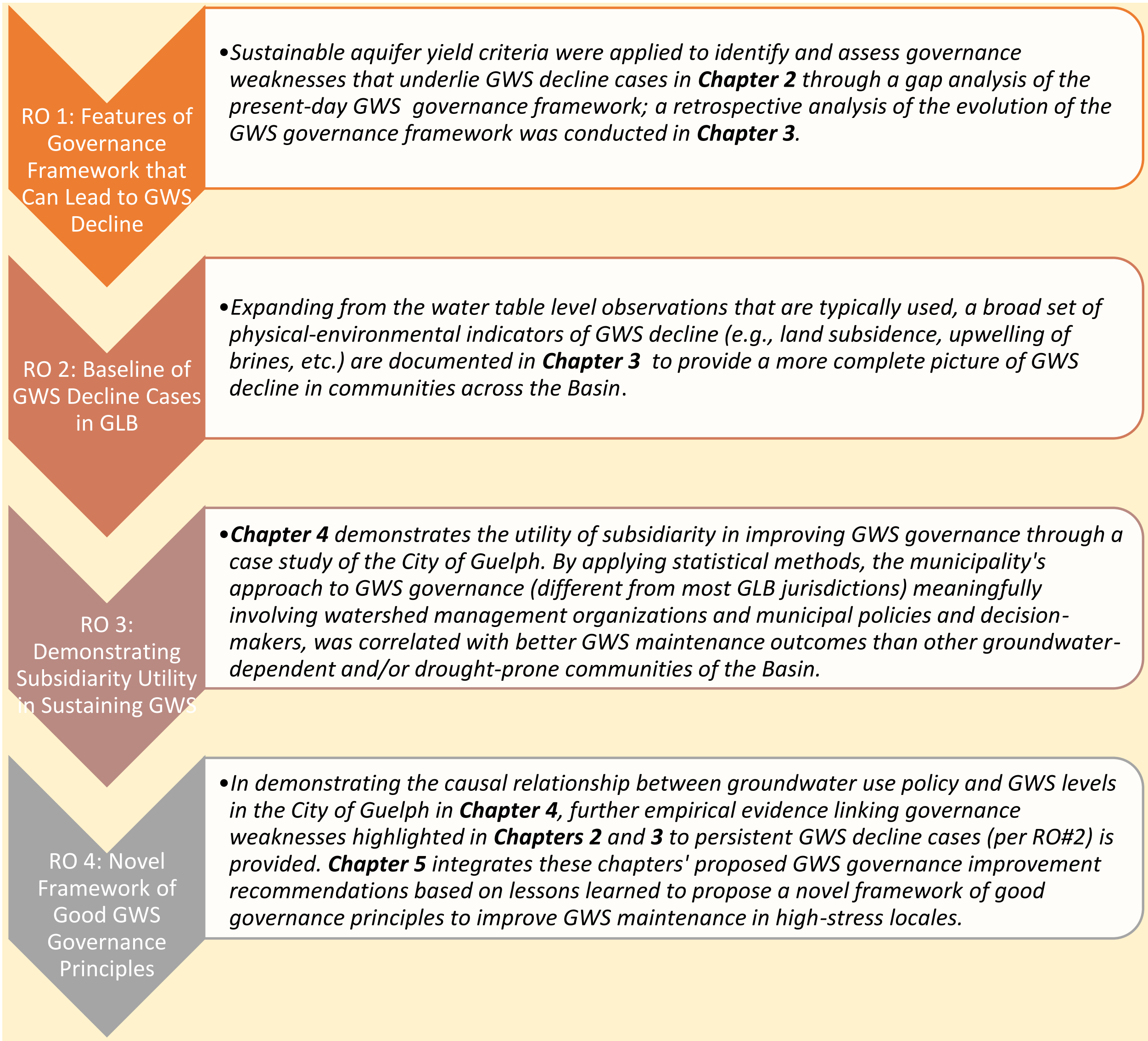
III. Demonstrate the utility of integrating subsidiarity in multilevel governance for improving the sustainability of GWS in high-stress locales; and

IV. Propose good governance principles for reformed GWS governance that directly addresses climate risks and growing groundwater demand in order to better sustain GLB groundwater quantity in vulnerable locations of the Basin.

5.2. Major Findings

This section describes the main findings of each chapter of the dissertation, explaining in detail how the findings realized the overall aim and research objectives. The analytical approaches applied in each chapter are summarized below in *Figure 12.*

Figure 12: Recap of Analysis and Methods Used to Achieve Research Aim and Objectives



I. Identify features of critical policies, governance processes and roles of key institutions and stakeholders between and across binational to municipal government levels in the US and Canadian jurisdictions of the Basin that can lead to GWS decline in aquifers supplying high-stress locales

Covered in *Chapters 2* and *3*, governance features were identified by applying physical-environmental requirements for sustainable aquifer yield as evaluative indicators to assess the degree to which the GWS governance framework considered the: (i) finite volume of groundwater that an aquifer can store (that is innately limited by its maximum storage capacity which is determined by geological characteristics); (ii) natural recharge of aquifers (determined by precipitation and influenced by changes in climate); (iii) environmental flows required to maintain dependent natural habitats and baseflows; and (iv) extent to which human withdrawals disturbed the natural equilibrium required to maintain GWS and other environmental flows and/or avoid unwanted GWS outcomes (Freeze and Cherry, 1979; Walton and McLane, 2013). As GLB aquifers store only 20 percent of the Basin's water resources, and are replenished at an exponentially slower rate than surface water resources (Pentland and Mayer, 2015), these sustainable yield considerations would need to be well-integrated throughout the governance framework to be adequate to maintain GWS in high-stress locales. *Chapters 2* and *3* assessed the extent to which these factors were integrated into multilevel policies and decision-making standards controlling groundwater use.

Chapter 2 appraised the present-day GWS governance framework, highlighting five critical governance features across GLB jurisdictions that can undermine groundwater security in vulnerable locales. The first finding was that the scopes of decision-making standards and policies insufficiently consider sustainable aquifer yield requirements. Instead, they appear to be better suited to surface water sustainability (Howard and Gerber, 2018) given their mostly identical prescriptions for governing groundwater and surface water use in spite of the substantial quantity and recharge differences between the Basin's groundwater and surface water resources.

This conclusion rests chiefly on the observation that most groundwater use governance controls apply to users withdrawing and/or diverting large, "bulk" quantities of GLB groundwater and that these bulk water volumetric thresholds for regulating groundwater use are considered to be too high to maintain GWS in high-groundwater-stress locales (Gosman, 2011). Bulk water users are typically defined as (i) exceeding 379,000 litres/day in a 90-day period; (ii) all requests for diversions or consumptive uses outside of the Basin and intra-Basin transfers (except when in containers measuring 20 litres or less); and (iii) within-Basin water consumption exceeding 19 million litres/day in a 90-day period (Kilbert, 2019). This bulk water definition features in the *Great Lakes-St. Lawrence Basin Sustainable Water Resources Agreement* (*2005 GLSWRA*) and the US Government's *Great Lakes Compact* (*2008 Compact*), which allowed GLB states to adopt many *2005 GLSWRA* policies. It also features in many state and provincial laws, except for Illinois, Indiana, Michigan and Ohio, which have far greater bulk water use volumetric definitions than those set in binational and federal policies (Weekes, Krantzberg and Vizeu, 2019).

Chapter 2 found that there are also large groundwater-using sectors that have no controls at all and completely disregard sustainable aquifer yield concerns. Most notably, state/provincial statutes typically allow unrestricted groundwater use from the agricultural sector (IJC, 2010), which is widely considered to be the most intensive groundwater-using industry. It is no coincidence that GLB communities experiencing groundwater insecurity have been engaged in long-term groundwater pumping for irrigation such as in Michigan's Lower Peninsula (Curtis, Sampath and Liao, 2015) and Ottawa County abutting northern Lake Michigan (Curtis, Liao and Li, 2018).

Another supporting finding is that multilevel GWS governance measures largely ignore the cumulative impact that smaller groundwater withdrawals can have on aquifers over time (Reeves, 2011), undermining groundwater security in vulnerable communities. This is because governments consider these quantities of use to be "reasonable," not requiring any volumetric controls (Dellapenna, 2014). This is evidenced in an array of policies, ranging from those allowing groundwater exports from the Basin in containers of 20 litres or less (per the *2005 GLSWRA, 2008 Compact* and state/provincial laws); to the free trade of groundwater in exports per the *2020 United*

States–Mexico–Canada Agreement (*2020 USMCA*); to the lack of controls for groundwater pumping below the "bulk" water use rates in all GLB states/province for all groundwater-using sectors (GLC, 2016; Kreutzwiser, Durley and Priddle, 2013). Moreover, there is wide disregard of the temporal dimension of sustaining GWS (Byun, Chiu and Hamlet, 2019) with many jurisdictions omitting mandatory measures to control groundwater use during droughts. Notable exceptions are Pennsylvania, which has the longest-standing GLB law restricting groundwater use during droughts—the *1978 Emergency Management Services Code* (35 Pa.C.S. §7101 et seq.)—and Ontario, in the *2002 Ontario Low Water Response Act.*

The second major GWS governance weakness in *Chapter 2* is the lack of inducements for groundwater use efficiency. Except for Ontario (*Ontario Regulation 225/14*) and Minnesota (*Minnesota Statutes, section 103G.801*), no GLB state has set a smaller volumetric definition for bulk water than the *2005 GLSWRA* and *2008 Compact*. In addition, only Ontario and Minnesota have differentiated the volumetric definitions of "bulk" surface water and groundwater, setting lower volumetric thresholds of groundwater use requiring a permit. In addition, most GLB states have instituted voluntary guidelines for water use efficiency. Only Ontario, Pennsylvania and Indiana (*Indiana GLB Water Management Rule 312 IAC 6.2*) have mandatory water use efficiency measures, but these are limited to industrial users (in Indiana) and during droughts.

The lack of groundwater use efficiency incentives is also evidenced in the paucity of economic policy tools that reflect the true value of the resource and the degree of risk to its availability (Sandhu *et al.*, 2020). As GLB groundwater is a relatively scarce resource compared to GLB surface water resources, the low (or sometimes non-existent) pricing of PTTWs and municipal water supply tariffs, as well as the use of identical pricing structures for water sourced from both aquifer and surface water reservoirs, does not promote use efficiency (Nelson *et al.*, 2016). These policies have led to the assessment that the Basin's groundwater resources are underpriced and overused (CEC, 2017). As overall water use in the Basin is still amongst the highest globally (Bruneau, Dupont and Renzetti, 2013), there is room for improving conservation and efficiency measures that can safeguard GWS in drought-prone and/or groundwater-dependent locales.

The third governance weakness found in *Chapter 2* is that multilevel governance processes do not contain sufficient measures to enforce, monitor and/or discourage non-compliance with groundwater use rules. One illustration of this governance gap is the significant variation in the degree to which the already-meagre policy and decision-making prescriptions for GWS governance in the *2005 GLSWRA* have been incorporated into state and provincial policies. The *2008 Compact* mandates only that GLB states adopt the *2005 GLSWRA* prescriptions "as much as possible," and Illinois is exempt from following them at all due to the 1980 US Supreme Court decision, *Wisconsin vs. Illinois, 449 U.S. 48,* which established the Chicago Diversion. Considered together with the limitations imposed by the *1787 US Constitution* and *1986 Omnibus Water Resources Development Act,* GLB states are under no legal obligation to adopt the policy prescriptions agreed to by the US and Canada in the *2005 GLSWRA* (Karkkainen, 2013).

Instead, as the *2008 Compact* is currently written, the GLB states are only legally bound to each other in following GLB water use prescriptions, and in effect, they continue to act in good faith with the Canadian government and province of Ontario in consulting and cooperating on GLB water use. The *2005 GLSWRA* imposes no legal consequences on GLB states for failing to consider the oppositions of the Great Lakes premiers.

Further supporting evidence of insufficient governance measures for discouraging non-compliance with GLB groundwater use rules was also observed in the over-reliance of the GLB states and province on self-reporting to track compliance with PTTWs. The only jurisdictions with some form of inducement are Minnesota, which requires the installation of water use tracking meters (*Minnesota Statutes, Section 103G.801*), and Pennsylvania, which has fines for breaking PTTW terms (*Pennsylvania Title 32 PS 817.21 Forests, Waters and State Parks Statute*).

Regarding the fourth governance feature that can undermine GWS preservation in vulnerable locations, *Chapter 2* found that multilevel policies and decision-making standards inadequately balance competing groundwater conservation and commercial interests. Supporting evidence is noted in the alignment of the *2005 GLSWRA* policy that allows the diversion of GLB water without regional review in containers less than 20 litres, and in the free trade policies of the *1994 North American Free Trade Agreement* (*NAFTA*) and *2020 USMCA*. Free trade agreements prohibit subjecting the use of groundwater embedded in products to regulation under any domestic laws, including those designed for the sustainable governance and/or conservation of GWS. Moreover, free trade agreements have legal redress if water-using industries perceive prohibitions to free trade. With companies increasingly attracted to the Basin, in part due to its cheap, clean and abundant groundwater resources, competition for and depletion of groundwater resources has been found to be accelerating in communities already dependent on the resources and/or prone to droughts (Schaffer, 2008; Wolfe, 2014).

On the fifth and final GWS governance gap found in *Chapter 2*, the evidence suggests that a top-down approach to GWS governance can inhibit the formulation of groundwater use regulations tailored to the unique needs of drought-prone and/or groundwater-dependent communities. As these needs can vary over time and space, sustainable GWS management is best when informed by a governance approach that considers the unique physical-environmental constraints of groundwater resources that vary according to the environmental and hydrogeological settings of aquifers. This is typically facilitated when governance scales are matched with those of aquifers (Stoa, 2014). In this context, as GLB municipalities and watershed management organizations (WMOs) are typically excluded from meaningful engagement in policy- and decision-making impacting GWS despite the fact that their scales better match those of aquifers, sustainable GWS governance is undermined. With 263 municipalities and hundreds of WMOs conducting relevant scientific research and GWS monitoring of aquifers underlying the Basin's 186 watersheds (Reeves, 2011), the lack of subsidiarity in GWS governance undermines its effectiveness in drought-prone and/or groundwater-dependent locales.

In *Chapter 3*, sustainable aquifer yield evaluative criteria were again used in retrospective analysis of the more-than-one-century-old history of policies and decision-making standards leading up to the contemporary GWS governance framework. Its findings illuminate the past governance features that were insufficient for maintaining GWS in vulnerable locales and explain why and how these weaknesses persisted through the intervening years, remaining core elements of multilevel policies, decision-making standards and court decisions applied today. The analytical timeframe for policies directly controlling groundwater use spanned the establishment of the *1909 Boundary Water Treaty*, the first modern binational agreement on the governance of GLB waters, to the *2005 GLSWRA.* Policies creating the economic conditions and incentives under which users make decisions regarding groundwater use were evaluated up to the *2020 USMCA.*

The findings highlight that although the US and Canada have a long history of binational cooperation in governing the quantity of the GLB's waters, it has largely excluded the physical-environmental considerations necessary to sustain GWS, contributing to GWS vulnerabilities. Analysis revealed that this stems from the way in which the *Reasonable Use Rule* has been interpreted and applied to govern GLB water use over the years. Originating from 19th-century

English common law, it allowed landowners to withdraw groundwater below their properties without waste and/or without harmful impacts on neighboring users/landowners (National Research Council, 2007).

Interpreted differently across North America, in the GLB region, the definition of reasonable use has historically been contextualized by the *Underground Stream Doctrine*. Herein, groundwater wells are treated as surface diversions and groundwater flows considered "tributary" to surface water bodies. As such, the aim of preserving GWS has integrally been *for the purposes of* preserving surface water quantities (National Research Council, 2007). Evidence of better surface water preservation outcomes corroborates this and suggests that statutes and standards made over the years have been based on surface water physical-environmental sustainability needs. Examples range from increasing cases of GWS decline (summarized fully in *RO 2*) to water use efficiency studies showing that as of 2015, consumptive use of GLB groundwater had increased by 3 percent, while consumption of surface water had decreased by 15 percent (Pentland and Mayer, 2015).

Chapter 3 also found that the history of jurisprudence resolving GLB groundwater use conflicts has advanced the application of surface water policies to maintain GWS. As court rulings resolving GLB surface water disputes have had a more-established track record, these same legal precedents have customarily been applied in rulings resolving groundwater use conflicts (Eckstein and Hardberger, 2017). Moreover, court rulings applying the *Reasonable Use Rule* to resolve groundwater use complaints seem more concerned with maintaining the equitable use rights of landowners than with conserving GWS through the application of sustainable aquifer yield considerations. This is perhaps best illustrated by the *Bralts and Leighty* (no date) ruling in a Michigan court, which noted: "if a neighbor complains that your irrigation pumping is causing their well to go dry, a prudent response would be to offer to deepen their well and consider it an irrigation expense."

Evidence collated in *Chapter 3* also helps to explain why these policy patterns have persisted over the years, despite evidence that regulations and court decisions have been clearly better suited to safeguarding the Basin's surface water and/or did not encourage GWS conservation. Path dependency, in which governments initiate a particular policy track, making the costs of reversal or change extremely high (Cerna, 2013), was identified as the likely reason. Policy-makers depend on exceptional opportunities to break path dependency (Capoccia and Kelemen, 2007), and these instances have not yet surfaced in the discourse on GWS governance. Instead, policy-makers have had little incentive to change regulations, as groundwater insecurity has been a highly localized and location-specific problem so far (Morris, Mohapatra and Mitchell, 2008). Moreover, there has been no public pressure demanding governance reforms. The general public's water risk literacy has been traditionally low, lacking awareness of socio-environmental risks to groundwater availability (Sandhu *et al.*, 2019). To illustrate, as of 2008, merely 10 percent of Canadians believed fresh water supplies were vulnerable to climate change (RBC, 2017).

II. Develop a baseline of empirical evidence of GWS outcomes that have resulted from binational and multilevel power dynamics with an assembly of reported cases of persistent GWS decline in the GLB

The Great Lakes Regional Water Use Database has tracked regional water use since it was established in 1988 following the binational *1985 Great Lakes Compact*. However, the impacts of rising human use on aquifers, as well as the amplifying effects of climate change, are yet not adequately understood, as the regional database does not track groundwater-specific uses (Granneman and Van Stempvoort, 2016). The findings of *Chapters 2, 3* and *4* all indicate that the GWS impacts of these pressures are not yet fully tracked in drought-prone and/or groundwater-dependent GLB communities, while GWS decline is more likely observed in these communities (Feinstein, Hunt and Reeves, 2010). The picture of the true extent of location-specific cases of GWS decline is incomplete, partly because water table recording is the predominant method used to monitor GWS by the Canadian Geological Survey, US Geological Survey, state and provincial well networks and well license and/or PTTW holders (Kornelsen and Coulibaly, 2014).

Chapter 3 sought to provide a more complete baseline of GWS vulnerability, taking an expansive look at more indicators of GWS decline. Apart from the long-term lowering of groundwater table levels, these indicators include gravity differentials from satellite readings (Huang *et al.*, 2010); waning stream baseflows (Holtschlag and Nicholas, 1998); the deterioration of groundwater-dependent habitats (Reeves, 2011); land subsidence—the gradual lowering of land over time (Galloway, Jones and Ingebritsen, 2000); and upwelling of brines in pumped groundwater (Curtis *et al.*, 2018). These indicators were found via review of relevant scientific and GWS management institutional reports and survey responses from water management institutions in the GLB states/province. The main findings are as follows: (i) at the Basin-scale, long-term satellite monitoring has estimated a current, average GWS loss of 3.8 ±2.3 km^3/year (Huang *et al.*, 2010); (ii) survey results of reported incidents of these indicators suggest that waning GWS is actively occurring in roughly 10 percent of the GLB's 263 municipal jurisdictions.

III. Demonstrate the utility of integrating subsidiarity in multilevel governance for improving the sustainability of GWS in high-stress locales

The GLB covers an area of 780,000 km^2 comprising 186 watersheds (Coon and Sheets, 2006) housing aquifers of differing hydrogeological characteristics and climatic settings. In this context, the findings of *Chapters 2, 3* and *4* all assessed the top-down approach to developing and applying policies and standards impacting GWS as inflexible to the variety and changeful nature of local groundwater needs, as well as the unique physical-environmental settings of aquifers. They have all linked this approach to groundwater insecurity outcomes, highlighting that governance processes and scales do not match the socio-environmental needs of groundwater-dependent and/or drought-prone GLB communities.

In *Chapter 4*, the role of adaptive governance and the process of subsidiarity were explored as an alternative GWS governance approach, assessing how this has been operationalized in the City of Guelph, Ontario. Subsidiarity is the organizing principle of delegating greater governance roles to the least-centralized government level with sufficient political power and capacity. The process allows for adaptive governance, whereby institutional capacities and governance processes are more likely to be flexible to changeful local needs and socio-environmental conditions, as their scales and governance processes more closely match those of natural resource systems (Stoa, 2016).

As Ontario is the only GLB jurisdiction to legally require municipal involvement in PTTW decision-making (*2001 Ontario Municipal Act*), municipalities in the GLB states play a mainly indirect role in safeguarding GWS through land use planning that impacts natural recharge (Weekes and Krantzberg, 2021). The case study of the City of Guelph presented in *Chapter 4* provides one of the few examples of adaptive governance and illustrates the benefits of including GLB municipalities in groundwater use governance through the subsidiarity process. Despite being exclusively groundwater dependent, located in a drought-prone area and ranking amongst the fastest-growing metropolitan areas of Ontario, the City has managed to maintain its GWS. The case study comprised a linear correlation analysis to assess the extent to which policy (indicated with historical pumping rates) impacts GWS (indicated with historical groundwater levels of aquifers within the City of Guelph) as opposed to precipitation. The results show that policy has been a greater determinant of GWS than precipitation, suggesting that the City has been able to maintain stable GWS despite growing human and climate pressures due to its unique GWS governance features.

In so doing, *Chapter 4*'s findings underscore the possibility that the overall top-down approach to GWS governance—lacking meaningful participation from WMOs and municipalities—can stymie adaptive governance, undercutting its potential to address GWS vulnerabilities. Based on the case study, the first governance feature unique to the City that may be instructive in improving GWS governance elsewhere in the Basin is that Ontario has set lower volumetric water use rate definitions for bulk water than those outlined in the *2005 GLSWRA*. The province has also set groundwater use permit thresholds below those required for surface water, which is more reflective of sustainable aquifer yield considerations than most other GLB jurisdictions.

The second instructive governance feature is that the City is able to participate in decisions granting PTTWs to bulk water users within its jurisdiction. This enables the City's unique groundwater needs and the physical-environmental limits of underlying aquifers to factor into the decision-making process. The City is empowered to make science-based policies and decisions on GWS through close collaboration with the Grand River Conservation Authority, one of Ontario's system of conservation authorities that conducts GWS research and monitoring and is staffed by local municipal and technical personnel. Another feature is that the City has its own mandatory water use bylaws (which most GLB municipalities do not have) that are adaptive to climate conditions, progressively restricting groundwater use based on drought intensity. The fourth feature is that the City ensures compliance with groundwater use rules and PTTW conditions with a rigorous monitoring program and a system of fines. Finally, the City mandates general water use efficiency and has also set an ambitious target of curtailing water use to 157 litres per person per day by 2038 in its planning for an increasing population and corresponding demand (GRCA, 2018).

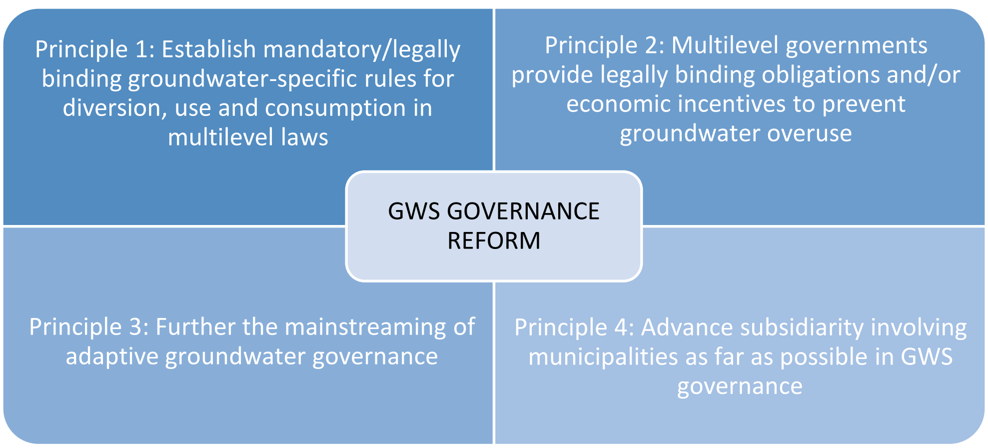
IV. Proposal of good governance principles for reformed GWS governance that directly addresses climate risks and growing groundwater demand in order to better sustain GLB groundwater quantity in vulnerable locations of the Basin

The control of groundwater use in transboundary basins has almost always been subsumed under rules devised for regulating surface water use. However, considering the current international progress on safeguarding the quantity of shared groundwater resources, the GWS governance framework in the GLB falls into the relatively progressive category of the world's treaties and binational agreements. As discussed above, multilevel governments have taken steps to advance sustainable groundwater governance with the historic focus on scientific research that, with sufficient political will, can inform polices and decisions promoting sustainability, social equity and economic efficiency in the use of stored groundwaters (Morris, Mohapatra and Mitchell, 2008).

However, the potential positive impacts that these features can have on maintaining GWS in groundwater-dependent and/or drought-prone situational contexts are muted by inadequate multilevel government collaboration that excludes WMOs and municipal institutions in most policy- and decision-making on groundwater use. The dissertation also makes clear the impacts of neglecting science when devising multilevel government water use policies, seen in the total omission of sustainable aquifer yield requisites in multilevel governance approaches. To address this, looking ahead, policy-makers would need to better appreciate the widely varied spatio-temporal aspects of maintaining GWS throughout the Basin, the subtle nuances between surface water and groundwater systems and the impacts of changing climate and human pressures to avert proliferating groundwater availability risks.

Taking this into account, *Chapters 2, 3* and *4* all conclude with recommendations to reform the Basin's GWS governance framework. Integrated into a conceptual whole, as shown in *Figure 13,* four essential principles designed to bridge governance gaps in order to better support GWS in groundwater-insecure communities have been distilled. Describing key actors and appropriate implementation measures for governance reform, proposals applicable to the range of socio-ecological settings in which groundwater-dependent and/or drought-prone communities are located have been deduced.

Figure 13: Principles for a Reformed Multilevel Groundwater Quantity Governance Framework



- *<u>Principle 1: Establish mandatory/legally binding groundwater-specific rules for diversion, use and consumption in multilevel laws</u>*

Fundamental policies controlling groundwater use and impacting GWS have not changed much from their origins in 19th-century court decisions (Dellapenna, 2013). Supported throughout the findings of this dissertation (particularly *Chapter 3*), the longstanding application of the *Underground Stream Doctrine* underlies why multilevel policies and decision-making standards controlling GWS are identical to those of surface water. This also helps to explain why these standards have always been better suited to surface water sustainability (National Research Council, 2007). The *Absolute Ownership Rule* also underpins why groundwater use below defined bulk water thresholds does not attract conservation regulations, as it has been inherently tied to private property rights (McKay, 2007).

The original court decisions that developed these legal principles were premised on an insufficient understanding of aquifer extents and groundwater storage quantities, given the state of science in the 19th century (Roman and Ferris, 1989). This can be summed up in the 1843 *Chasemore v. Richards* (1843-60 All E.R. 77, 81-82 H.L. 1859) ruling, which declared that it was impossible for the courts to limit "water percolating through underground strata, which has no certain course and no defined limit, but oozes through the soil in every direction in which the rain penetrates." Today's scientific knowledge of groundwater hydrology across the Basin has certainly improved, meriting a corresponding modernization of legal principles and customary jurisprudence.

There have been significant advances in the hydrogeological understanding of the GLB over the years, with regularly-published studies from the USGS, CGS, state and provincial institutions, academia and conservation authorities, and publicly available real-time readings of GWS levels in some well monitoring networks. There have also been important changes to the direction of groundwater research at the binational level: *Annex 8* of the 2012 amendment to the *Great Lakes Water Quality Agreement* called for greater coordination of groundwater science and management actions and to "publish a report on the relevant and available groundwater science" by February 2015. This was fulfilled in the IJC (2016) report "Groundwater Science Relevant to the Great Lakes Water Quality Agreement: A Status Report" (Granneman and Van Stempvoort, 2016), which provides important updates on the state of GWS across the Basin.

Twenty-first-century hydrogeological science calls for 21st-century groundwater law. The modernization of groundwater governance fundamentally boils down to the revision of legally binding terms controlling pumping rates (Kreutzwiser, Durley and Priddle, 2013), the most important of common law, statutory law and policy in North American institutional historicism controlling GWS. As broad guidance, policy-makers across government levels would need to make commitments to differentiate the volumetric use rate triggers requiring permits for bulk groundwater and surface water withdrawals. In addition, setting bulk withdrawal, consumption and diversion limits that are far below surface water limits would better reflect groundwater's relative scarcity and unique socio-environmental risks. A bottom-up approach to setting these limits, based on the physical-environmental limiting factors for GWS that are unique to local the groundwater flow systems of the Basin, would be a more sustainable and science-based approach. As these responsibilities have usually been the remit of binational to state and provincial levels of government, relatively recent legislative amendments in Ontario (*Ontario Regulation 225/14*) and Minnesota (*Minnesota Statutes, section 103G.801*) that have reduced and/or differentiated groundwater and surface water "bulk" definitions provide the best-case examples. These lessons are transferable to any government level or jurisdiction in the shared GLB context.

A significant bulk groundwater policy blind spot exists for the agricultural sector. With groundwater providing the majority of irrigation water, agriculture is a significant groundwater-using sector that is almost 100 percent consumptive (Gosman, 2011) and furthers permanent water loss from GLB aquifers with the virtual water trade in agricultural exports (Mayer, Mubako and Ruddel, 2016). The findings of *Chapters 2*, *3* and *4* all point to the lack of bulk groundwater use regulations across GLB jurisdictions that over the years has caused the majority of groundwater insecurity incidents to occur in agriculture-intensive communities (Weekes, Krantzberg and Vizeu, 2019). While the importance of food production is undeniable, with growing climate and human demand pressures, its future development must be compatible with groundwater conservation goals to ensure that the resource is sustainably utilized for optimal (not maximal) social and economic benefits (Mayer, Mubako and Ruddel, 2016). Though environmental impact assessments are already in place in many PTTW decision-making processes, one good way to manage agricultural groundwater demand could be to expand on these screening measures for new and/or increased bulk water uses from the agricultural sector. Doing so would enable the avoidance of undesirable consequences while optimizing food security.

While lowering bulk water use policies and setting environmental impact standards are well within the remit of multilevel governments, these institutions have very limited legal options for regulating groundwater uses that fall below bulk water definitions, even when such regulation aims to conserve GWS for the greater public good (Kreutzwiser, Durley and Priddle, 2013). In the case of multilevel statutes, smaller groundwater uses have traditionally been deemed "reasonable" (per the *Reasonable Use Rule*) and mainly take place within private land using smaller capacity wells. Additionally, private/domestic groundwater use mainly proceeds without volumetric or temporal use limits due to the traditional tying of groundwater access rights to land ownership per the *Absolute Ownership Rule* (Nelson and Quevauviller, 2016).

Invoking the *Public Trust Doctrine* to set volumetric limits on "reasonable" groundwater uses for the greater public good is not typical, as in many jurisdictions, groundwater is not defined as a natural resource type protected under existing public trust laws, e.g., Indiana's *2003 Water Rights and Resources Act* (Indiana Code 14-25-1(1)). In terms of court decisions, with the panoply of multilevel environmental statutes, in some jurisdictions (e.g., Ontario), public nuisance claims have "limited potential as a means of vindicating the interests of environmentalists" and thus limit consideration of public trust principles in rulings on groundwater use conflicts between private well owners (Roman and Ferris, 1989).

Presently, the most feasible legal means multilevel governments have to set mandatory conservation standards for "reasonable" groundwater uses may be through emergency groundwater use laws during droughts. The vast majority of GLB jurisdictions have such measures in place, but only on a voluntary basis; where they are mandatory, they are often executed through the powers of governors and/or premiers to declare public emergencies. One good example is Pennsylvania's *1978 Emergency Management Services Code* (35 Pa.C.S. §7101 et seq.). There are very few, albeit instructive, cases where judicious groundwater use has been made mandatory via other legal instruments. Among them, the City of Guelph's bylaws may be informative, particularly the *2014 Outside Water Use Bylaw 19714*, which requires efficient outside water use corresponding to three levels of intensity of dry weather periods. Indiana's water use efficiency laws specifically made for the industrial sector may also be instructive (*Indiana Great Lakes Basin Water Management Rule 312 IAC 6.2 e*).

- <u>*Principle 2: Multilevel governments provide legally binding obligations and/or economic incentives to prevent groundwater overuse*</u>

Resource conservation policies rarely achieve desired outcomes unless there is a system of monitoring, incentives and disincentives to ensure enforcement (Ostrom, 1990). The paucity of these measures across multilevel groundwater use policies is well documented in *Chapters 2* and *3*. *Chapter 4* provides a best practice example of monitoring and incentives that have proven successful in encouraging judicious groundwater use, resulting in long-term GWS maintenance. Based on these lessons, recommendations applicable to multilevel policies are explained below.

As mentioned above in *RO 1*, at the binational level, in the case that GLB states choose to allow groundwater uses that are not compliant with *2005 GLSWRA* policies, there is no legal obligation to seek agreement from Canadian premiers. Although protections for Great Lakes waters have progressed over the past century, as it stands today, the *2005 GLSWRA* remains effectively a US–Canadian good faith agreement providing insufficient protection of the water use interests of the Canadian jurisdictions within the Basin, as they are not part of the *2008 Compact*.

Moral obligations from good faith agreements may not be able to insulate Canadians from extreme droughts and other water shortage crises that are expected to progressively influence water politics in the United States (Kane, 2017). Western and southwestern states face worsening water supply issues and droughts are expected to be prolonged into the next century (Hall and Stunz, 2008). This will lead to increased desertification and reduced snowpack, which is essential for providing the headwaters of many river and groundwater flow systems in many Colorado River Basin states. Many newspaper articles and ideas have been pitched to pipe GLB waters to this region to shore up dwindling water supplies. So far, they have been dismissed, but with increasing droughts and growing populations in the US southwest, concerns are rising about how long that will last (Annin, 2018).

Water quality crises are also expected to be on the rise. The Waukesha, Wisconsin GLB water diversion was prompted by prolonged groundwater pumping that led to the upwelling of radium that contaminated drinking water supplies (Choi *et al.*, 2012). It was granted after a protracted process conducted via the prescribed consensus-based approach as outlined in the straddling community exception of the *2005 GLSWRA* (GLSLCI, 2018). While granting the Waukesha diversion was already contentious and hotly contested, though it followed the prescriptions of the *2005 GLSWRA*, rising water quality issues further afield will increase challenges to the general prohibition on diverting any quantity of GLB waters. To illustrate, if an increased diversion from Lake Huron is needed to address the damage to the Flint, Michigan water supply system, governors may choose to disregard Canadian interests given the urgent Legionnaires' disease public health crisis (Kane, 2017). With aging water distribution infrastructure raising the spectre of lead contamination across the United States (Karkkainen, 2013), more “Flint-type” crises are expected to occur, inexorably changing the contours of US water politics.

The Watershed Council (2020) has documented trends in legal challenges and requests for GLB water resources for uses outside of the Basin (*Table 13*), underscoring the external geopolitics that will increasingly impact GWS. So far, three of the nine requests have been granted.

Table 13: Requests for Diversions and Exports of Great Lakes Water from the 1909 BWT to 2020 USMCA

YEAR	BULK GLB WATER RESOURCE REQUEST
1981	A request from the Powder River Coal Company to divert Great Lakes water to Wyoming to feed a coal slurry pipeline to the Midwest is denied.
1982	The U.S. Army Corps of Engineers recommends that a request for a diversion of Great Lakes water to recharge the Ogallala Aquifer (spanning South Dakota to Texas) be denied.
1990	Approval for a temporary 3.2 million gallons a day diversion from Lake Michigan for the public supply of Pleasant Prairie, outside of the GLB in Wisconsin, is granted on the provision that treated wastewater is returned to the Lake by 2010.
1992	Lowell, Indiana, is initially denied its request for a 2 million gallons a day diversion for public supply. This was later vetoed by the governor of Michigan.
1998	An out of Basin diversion from Lake Michigan of up to 4.8 million gallons a day for public supply in Akron, Ohio is approved.
1998	The Ontario Ministry of the Environment approves a request by the Nova Group to export 160 million gallons per year of Lake Superior water to Asia in shipping containers. The permit is later withdrawn because of protest by Great Lakes governors and citizens.
2006	An application for 1.83 million gallons a day of Lake Michigan water for parts of the New Berlin, Wisconsin community outside of the GLB is made and approved.
2016	A request to take 8 million gallons a day of Lake Michigan water is granted to the straddling community of Waukesha, Wisconsin.
2018	Racine, Wisconsin (a community within the GLB) is granted a permit for Racine and Foxconn to use 7 million gallons a day from Lake Michigan. Some 70% of the water is diverted to Foxconn, taking it outside the Basin.

Considering these external pressures, a binding binational agreement, with legal consequences and penalties for parties that do not comply with its terms, is especially important given the disparity in the representation of interests between the US and Canadian portions of the Basin (Karkkainen, 2013; Karkkainen, 2006). Some 40 percent of the Basin population resides in the Canadian portion (Chaloux and Paquin, 2013), yet only two of the ten votes within the Great Lakes Commission are Canadian, and a binding agreement alone will not compensate for this underrepresentation. Therefore, to allow for such significant policy changes, an exceptional circumstance will likely need to occur to break the current policy path (Cerna, 2013).

For the longest while, Canadians have subscribed to the myth of water abundance, typically registering low water risk literacy (Sandhu *et al.*, 2020; Kane, 2017). However, the tenth edition of the Royal Bank of Canada (2017) “Water Attitudes Study” reveals slow changes in public attitudes and perceptions of water risks. Encouraging trends are as follows: (i) more than 50 percent of Canadians “strongly agree” that water is a critical part of Canada’s national identity; (ii) 70 percent believe that climate change will have a negative impact on Canada’s water resource availability; and (iii) Canadians generally believe that the environmental impacts of increasing consumptive water uses will become increasingly pressing in urban communities and municipalities in ten years’ time. There is significant opportunity to capitalize on these trends through investments in public awareness campaigns on groundwater quantity risks, which in time could provide sufficient public pressure to engender the aforementioned policy changes.

On encouraging water use efficiency, Canadian municipal water utilities generally consider water supply tariffs as a means to generate revenue as opposed to a policy tool to signal scarcity or to engender efficient water use. Consequently, Canadians pay 70 percent of the true cost of their municipal water supply (CEC, 2017). The case study of the City of Guelph in *Chapter 4* demonstrates the utility of incentives in groundwater conservation. Complimented by rigorous monitoring and enforcement plans that discourage non-compliance, such as ticketed fines in the case of the City of Guelph (COG, 2019), such inducements could be most appropriate across the GLB's municipal water supply networks that rely on groundwater sources. Other incentives such as encouraging the installation of water efficient plumbing and charging inclining block rates can also incentivize water conservation in groundwater-insecure locations (Bruneau, Dupont and Renzetti, 2013). Some of Ontario's municipalities have applied these measures, resulting in a drop in residential water use from 343 L/day/capita in 1999 to 201 L/day/capita in 2016 (Statistics Canada, 2016).

- *Principle 3: Further the mainstreaming of adaptive groundwater governance*

Despite progress in groundwater science in the GLB, there remain many unknowns, particularly in the interactions of groundwater and surface water bodies as well as flow rates and directions of less-studied aquifer systems (Granneman and Van Stempvoort, 2016). Coping with these uncertainties requires an iterative approach that allows governance policies and decisions to be made in tandem with a program of environmental monitoring with the long-term goal of reducing uncertainty.

Though the term "adaptive governance" is included in the text of binational and state and provincial groundwater use policies, practicing adaptive governance is challenged by the current top-down approach to GWS governance. The lion's share of GWS governance roles are accorded to provincial and state governments, whose wide geographic scope challenges their flexibility in responding to unique aquifer needs and conditions and influences the speed at which they can respond to environmental changes and/or threats (Stoa, 2016), stymieing their capacity for iterative decision-making. The inclusion of municipalities in PTTW decisions in Ontario per the *2001*

Ontario Municipal Act is a step in the right direction. As the only GLB state/province mandate to include consideration of local communities in bulk groundwater use permitting decisions (allowing local aquifer physical-environmental sustainability needs to be taken into account), this policy provides a replicable approach towards further mainstreaming adaptive governance throughout the Basin.

- *Principle 4: Advance subsidiarity involving municipalities as far as possible in GWS governance*

So far, the framework of good GWS governance principles provides guidance on needed policy reforms emphasizing interdisciplinary research, monitoring and incentives encouraging groundwater use efficiency, localized groundwater management and improving awareness of the true availability and unique risks to GLB groundwater resources to encourage policy reform. Missing so far are recommendations to improve multilevel governmental partnerships and engagement with local stakeholders given the widespread exclusion of municipalities and WMOs from participation in groundwater use governance. Evidence from *Chapter 4* suggests that the top-down approach to GWS governance may be missing important opportunities to leverage the potential improvements to groundwater conservation proffered by this governance level.

The findings in *Chapters 2, 3* and *4* argue strongly that state and provincial institutions are too far removed from the local communities they serve and operate at too large a scale compared to the groundwater resource systems they are charged with sustaining. As such, concerted efforts to deepen subsidiarity in GWS governance are recommended. Critically, this would involve the establishment of municipal bylaws governing groundwater use, particularly during droughts, given municipalities' ability to closely monitor for compliance with regulations. Another avenue for subsidiarity involves improving meaningful engagement with municipalities in PTTW decision-making. Due to their jurisdictional scale, municipalities are better positioned to communicate their communities' groundwater needs. WMOs, with their traditional focus on groundwater research, could provide science-based inputs factoring in local aquifer physical-environmental constraints in PTTWs.

Consultation with WMOs such as Ontario's system of Conservation Authorities and the wider scientific community is needed to set sustainable, science-based groundwater use rates and further other conservation efforts tailored to the physical-environmental requirements of local groundwater flow systems. As such, engaging municipalities and WMOs in policy- and decision-making impacting GWS should be backed up by investments in improving their technical capacities. It is essential for higher-level governments to invest in improving their technical capacities in three core areas: (i) conducting groundwater research; (ii) sustainable groundwater use permitting; and (iii) monitoring local aquifer levels and their communities' groundwater use. This is partly because sustainable groundwater use permitting should be explicitly linked to land use zoning municipal bylaws, as these are not currently well aligned (Cohen, 2009). As learned from the case study of the City of Guelph, source water protection initiatives have entailed mapping recharge zones and prohibiting new settlements in these areas. The benefits of aligning PTTW policies with land use planning could include prohibitions and/or special environmental impact assessments for these at-risk areas.

- *Recommendations for implementation of good governance principles*

The proactive approaches suggested in the good governance principles outlined above are aimed at addressing current cases of groundwater insecurity and preventing further proliferation of the issue given growing human and climate stressors. However, the vast majority of international experiences in devising and implementing reforms to transboundary groundwater quantity governance show that they have been mainly developed for areas facing significant water availability threats. Fortunately, there has recently been precedent established for devising and implementing similar recommendations in international accords aimed at proactively addressing growing groundwater security in relatively water-rich regions where there is incomplete knowledge of the true extent of the groundwater insecurity proliferation like the GLB. A good example is the Guarani Aquifer Agreement between Brazil, Argentina, Uruguay and Paraguay. Although it was agreed upon in 2010, it was not until 2018 that it was ratified in all riparian states following a lengthy development process that is highly instructive to improving GWS governance in the GLB (Villar, 2016).

Key lessons include that the treaty was developed based on an inclusive and extensive consultative process spanning international development organizations, municipal to binational levels of government, academic institutions and private sector actors. It was also developed with strong science policy alignment, as the special-purpose Environmental Protection and Sustainable Development of the Guarani Aquifer System Project (2003-2006) was implemented, involving collaboration across riparian states, that improved the scientific knowledge on the use quantities, human and environmental stressors and hydrological and physical-environmental characteristics of the Aquifer system (Villar, 2016). These experiences underscore the importance of filling long-standing knowledge gaps and the inclusion of all stakeholders to enable progress towards groundwater-specific binational agreements in the GLB.

The Agreement is also instructive to the GLB context as it provides insights on the legally binding obligations that can be feasible for riparian states to implement while maintaining national sovereignty, which, until the 2005 GLSWRA, has been a constraining factor in the GLB. Guarani Aquifer states are obliged to conduct research on "studies, activities and works that contemplate the sustainable utilization of the Guarani System water resources'' to better conserve shared groundwaters. Towards this goal, the Guarani Aquifer Commission was established with a regional mandate to resolve conflicts, and to convene research and resource management projects to better sustain shared groundwaters. The GLB already has a similar arrangement in place with the Great Lakes Commission which includes this in its mandate. What is required is improved coordination and funding to undertake the research and studies needed to fill urgent GWS knowledge gaps.

Another legally binding obligation is that Guarani Aquifer states are required to regularly implement environmental impact assessments on groundwater use within national territories and on international boundaries. While this is currently not a feature in binational agreements impacting GWS in the GLB, the processes and policies used in the Guarani Aquifer Agreement could be instructive in future iterations of GLB agreements.

The fact that four countries agreed to a legally-binding consensus on a GWS governance framework to better sustain shared groundwater resources is testament to the region's progress in cooperation and collaboration. Similarly, implementing good governance reforms will depend heavily on the long-standing democratic processes and collaboration that are the cornerstones of US–Canadian natural resource governance (Chaloux and Paquin, 2013).

5.3. Original Academic Contributions

This body of research is not unique in sounding the alarm over intensifying groundwater uses and the inappropriateness of the laissez-faire approach that has characterized groundwater quantity governance in the GLB. Seminal research by Hodge (1989) explored the contemporaneous policy implications bearing on the appropriate regulation of human activities that affect groundwater; Cohen (2009) provided an overview of groundwater and land-use policy on sustaining GLB groundwater quantity and quality; and more recently, Saunders (2000) provided a gap analysis of the legal context governing GWS across the GLB states/provinces. Reeves (2011) raised the spectre of pumping rates that appeared to insufficiently consider the different storage capacities of the aquifers underlying the 186 watersheds of the Basin and their associated climatic and geological limits.

None of the above have evaluated multilevel GWS governance within the context of sustainable aquifer yield to assess whether policies are fit for purpose to maintain GWS increasingly vulnerable to rising demand and climate impacts. Based on this unique lens, this dissertation yields several contributions to the literature on groundwater quantity governance in international basins, with specific applicability to vulnerable situational contexts in the GLB.

I. A comprehensive review of the policies impacting groundwater storage from the binational to municipal level GLB government jurisdictions

Most of the literature on GLB water policy analysis pertains more to water quality issues than water quantity issues. Moreover, aside from a law review done by Saunders (2000), comprehensive analyses of policies pertinent to maintaining water quantity have not differentiated GLB surface water and groundwater issues. With the progress made in binational laws governing water use, particularly with the *2005 GLSWRA*, the analysis in *Chapters 2–4* provides an update to the literature on this topic. It also further dispels the “myth of water abundance” in the GLB, shining light on the temporal and sub-watershed physical-environmental considerations for GWS sustainability and the features of multilevel policies in need of improvement to address these issues.

II. A comprehensive examination of the state of monitoring sub-watershed scale occurrences of groundwater quantity decline indicators in the GLB

While the literature has documented groundwater decline mainly as a function of persistent reduction in groundwater table levels, *Chapter 4* sheds light on how widespread localized GWS vulnerabilities are across the GLB. It contributes this by reviewing reports of all indicators of groundwater decline, which aside from groundwater table levels include the destruction of groundwater-dependent ecosystems, habitats and ecosystem services; falling stream baseflow levels; land subduction; and the formation of sinkholes and/or cavities in sedimentary geological settings. These findings imply the importance of taking other indicators into account when monitoring GWS as well as the value of investing in GWS monitoring programs.

III. A unique correlation-based method to evaluate the performance of groundwater use policies in maintaining GWS in sub-watershed scale aquifers

As the causal relationship between policy and natural resource availability can only be established via statistical methods, *Chapter 4* provides a replicable method for ascertaining the relationship between groundwater use policy and GWS in certain conditions. We applied a simple linear correlation method—the Pearson's coefficient—to test the degree to which GWS policies determine long-term GWS in the City of Guelph, Ontario. The results imply that policy is a much greater determinant than precipitation in maintaining GWS in that groundwater-dependent community, enabling a targeted deduction of policy features that impact GWS sustainability.

A suitable proxy for policy was found in historical pumping rates set by Ontario's PTTW program, which is based on multilevel groundwater quantity policies. We used composite hydrographs showing an average of groundwater table levels in all aquifers used by the community as a proxy for GWS. This was feasible given the limited hydrological connection with other groundwater flow systems and nearby watercourses, which limited the practicability of using other GWS decline indicators. In so doing, the study demonstrates the feasibility of this approach in evaluating policy effectiveness when historical groundwater users and rates of use are known and precipitation data is available for aquifers in a pre-defined geographical and hydrogeological space.

IV. A novel framework of good groundwater quantity governance principles with multi-scale and multi-context applicability in the GLB

Based on the findings of *Chapters 2* and *3*, as well as a case study demonstrating the causal relationship between policy and groundwater quantity in *Chapter 4*, another important contribution of *Chapter 4* is the proposal of principles for groundwater quantity governance reform. Based on a comprehensive analysis of conditions in the GLB and a case study of a drought-prone region, the lessons are highly relevant and conservative, making them applicable to groundwater-dependent GLB communities in a range of social-environmental settings.

V. A well-researched case to develop standards for sustainable groundwater use that are separate from those governing sustainable surface water use

Across government orders and spanning water export or water conservation policies and institutional practices, identical regulations are generally applied to govern surface water and groundwater use. As these policies were found to be generally supportive of surface water sustainability, an important contribution of *Chapters 2*, *3* and *4* is the critical importance of developing groundwater use standards unique to local physical-environmental conditions for maintaining GWS. The chapters bring into focus the differing availability quantities, recharge rates and human-environmental threats between the two types of water resources and make clear that this policy blind spot is a fundamental contributor to proliferating GWS vulnerabilities in the Basin.

VI. Further support of the subsidiarity perspective in sustainable groundwater governance

Another important contribution of *Chapters 2, 3* and *4* is the importance of matching governance scales with environmental scales to result in sustainable natural resource governance. The findings of these chapters demonstrate that concentrating the vast majority of governance responsibilities at the state and provincial level of government is to the detriment of maintaining GWS in high-use contexts. With communities and aquifers generally existing at the sub-watershed scale in the GLB, the institutional flexibility of municipal jurisdictions can be better leveraged to improve GWS governance. The case study of the City of Guelph shows the utility of municipal governments in monitoring and sanctioning unsustainable groundwater uses, a feature that is generally lacking in the GLB, where groundwater overuse is inadequately disincentivized from the binational to municipal scales of government.

VII. Further support to proactive GWS governance in relatively water-rich regions

The majority of international agreements governing transboundary groundwater are in regions that are already facing severe and widespread groundwater shortages. International agreements also tend to ignore issues of governance and environmental scale, which can lead to the overlooking of localized, emerging groundwater insecurity issues. The dissertation highlights that even in relatively-water rich regions, localized cases of groundwater insecurity can occur, and identifies the multilevel and transboundary governance blind spots that can contribute to these problems. Given growing groundwater stressors with worsening climate and increasing human demand, proactive GWS governance approaches, regardless of water availability are becoming increasingly essential. Aligned with the recently ratified Guarani Aquifer Agreement, this dissertation adds to the body of work aimed at proactively addressing growing groundwater security in relatively water-rich regions where there is incomplete knowledge of the true extent of the groundwater insecurity.

5.4. Study Limitations and Directions for Future Research

There are two significant limitations of this dissertation that present opportunities for further future research to better sustain groundwater quantities in the GLB. They are as follows:

I. Assessment of multilevel policies governing groundwater quality

As the findings of this dissertation are strictly limited to groundwater quantity and consider policies directly related to groundwater use and aquifer recharge, assessments of the suitability of multilevel policies in safeguarding groundwater quality were omitted. With the implementation of *Annex 8* of the *2012 Great Lakes Water Quality Agreement*, there have been efforts to gather relevant science on groundwater. Building from these new findings, it could be useful to follow the approach of this dissertation, pointing out multilevel policy gaps to inform and target groundwater quality governance reforms to improve overall GLB groundwater sustainability.

II. Estimation of the total economic value of GLB groundwater as a strategy for improving groundwater use efficiency policy prescriptions and decision-making

In the review of multilevel policies and standards controlling groundwater use and impacting long-term GWS, it was found that while major strides have been made in the development of guidelines for water conservation, multilevel policies lack a robust framework of economic inducements promoting water use efficiency. Policies (i) exempt water uses for firefighting and private domestic water supply from requiring a permit (suggesting high prioritization); (ii) require permits beyond the same maximum allowable thresholds for both surface water and groundwater withdrawal with the same permit fees; and (ii) create enabling conditions for overuse with declining block rates to attract industry in some jurisdictions of the Basin.

Groundwater has an economic value, the sum of which can be estimated by collating the values it adds to various anthropogenic uses (e.g., irrigation, commercial, manufacturing, municipal water supply, mining, etc.) as well as the in-situ services and environmental flows it provides (e.g., protection from brines, maintenance of spring flows and watercourse baseflows, etc.). The lack of understanding of the economic value of groundwater has led to inefficient use, misallocation of the resource and inadequate attention to the maintenance of the quantity for future uses and in-situ services.

Billions of dollars have already been spent addressing water shortages by finding alternative sources of water and building new conveyance infrastructure. By conducting a study of groundwater's total economic value (TEV) with recommendations for integrating the TEV into multilevel policy, groundwater governance can be improved. Decision-makers would be better positioned to make sustainable decisions when they know the potential value trade-offs of decisions that have outcomes on long-term GWS. Even incomplete knowledge of the TEV provides decision-makers with insight into the trade-offs their water pricing decisions can have.

5.5. Research Reflections

The School of Earth, Environment and Society at McMaster University offers a unique academic environment which directly influenced the way in which this dissertation was undertaken. The School's focus on sustainability as a valuable goal that can be attained by policy and governance assessments contributed directly to the study objectives and analysis done in each core research chapter. In addition, the School's multidisciplinary research emphasis enabled identification of the study problem and appropriate research design involving the selection of useful analytical frameworks and methods in the course of this study.

Key assumptions of multidisciplinary research informed this dissertation. An important feature of multidisciplinary research that distinguishes it from other approaches is its application of methods that integrate "multiple knowledges" from practitioner and/or lay perspectives (Lang *et al.*, 2012; Pohl, 2010). These directly informed this study in its integration of surveys to elicit unique insights from practitioners obtained in the course of their work as well as in the review of draft papers by expert informants working within state and provincial GWS governance institutions.

The second defining aspect of multidisciplinary research is that it should address socially relevant problems (Pohl, 2010). This dissertation highlights sustainability issues and encourages a proactive approach to governance reforms to address groundwater insecurity risks. The pace of external geopolitics shaping water availability and use priorities outside of the Basin coupled with the internal human and climate pressures on limited GLB groundwater resources (though most of its residents remain unaware of these vulnerabilities) makes this a very real problem.

Pohl (2010) encourages that multidisciplinary research apply appropriate tools, regardless of discipline, to address practical problems. The conceptual frameworks, theories and methods applied in this dissertation borrowed from political science, hydrogeological science and civil engineering disciplines. As the School of Earth, Environment and Society fosters an environment that encourages the synthesis of insights from diverse perspectives, this academic training was essential throughout the course of this research, leading to my achievement of the completion of doctoral research.

5.6. References

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