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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

Khafi Weekes [1,*] and Gail Krantzberg [2]

[1] Faculty of Science, School of Earth, Environment and Society, McMaster University, Hamilton, ON L8S 4K1, Canada
[2] Faculty of Engineering, W Booth School of Engineering Practice and Technology, McMaster University, Hamilton, ON L8S 4K1, Canada; krantz@mcmaster.ca
* Correspondence: khafi.weekes@gmail.com

Abstract: How has groundwater use been historically governed by the binational to municipal government levels 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 amongst the largest freshwater stores in the globe, cases of groundwater shortages are increasingly being reported across GLB communities, raising questions on the fitness of governance approaches to maintain groundwater storage (GWS) with growing climate and human pressures. Applying retrospective analytical methods to assess the century-old collaboration of the United States and Canada 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 originally 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 multiple levels of government policymakers.

Keywords: groundwater storage; groundwater use; multilevel governance; agreement; transboundary basins; retrospective analysis; United States; Canada

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1. Introduction

With estimates ranging from 5585 km^3 to 4000 km^3 [1], groundwater accounts for roughly 20% of water stored in the Laurentian Great Lakes Basin (GLB). Groundwater fluxes maintain habitats and baseflows to tributaries of the five (5) Great Lakes [2]. It has also become increasingly vital for society, supporting the USD 6 trillion regional economy [3] of the eight (8) US states and the Canadian province of Ontario that are within the GLB's hydrological boundaries (Figure 1).

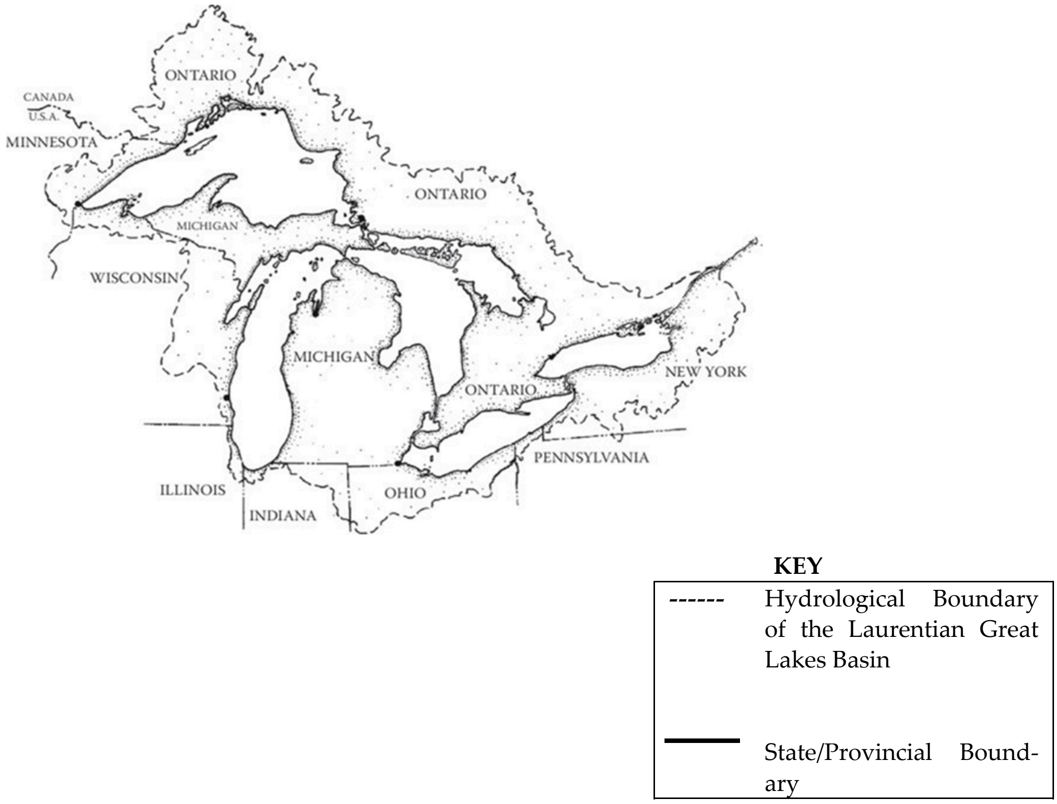

Figure 1. States and provinces within the Laurentian Great Lakes Basin hydrological boundary [4].

Rising populations with their attendant water demand and land use changes, coupled with climate change [5], are driving an emerging problem of persistent 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 [6]. Though this rate of decline pales in comparison to the overall water-richness of the GLB, the globe's largest surface 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 [7]. These trends are emerging as GWS—the volume of water that an aquifer holds at any given time within its voids and interstices—is fundamentally limited by an aquifer's storage capacity, which is based on its unique geometry and geophysical attributes [8]. While the quantity of GWS can fluctuate seasonally, as it is a derivative of a predefined rate of inflow from artificial recharge and/or precipitation, and outflow via natural discharge to surface water bodies and/or pumping, it can be permanently drawn down if subject to long-term overuse and reduction of recharge with climate change and land uses that increase impermeable surfaces [8].

GWS governance, involving planning, coordinating, policy making, implementation, and monitoring of policy outcomes [9], provides the means by which groundwater use may be managed, and socio-environmental stressors on GWS addressed. Normatively, long-term GWS decline indicates that governance may be 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 can be considered sustainable [10,11]. In these cases, consideration is placed on maintaining sustainable aquifer yield—the volume of groundwater that can be withdrawn from aquifer systems that avoids unacceptable environmental, socio-economic, and legal consequences [12]. Determining sustainable yield requires strong science–policy alignment as policymakers must consider the water balance of the overall hydrological system, uncertainties in quantifying GWS with spatial and temporal variation, and how human uses can impact GWS over time [12].

Given the GLB's transboundary basin settings, policies and decision-making standards impacting GWS (also known as the "GWS governance framework") are contained in binational-to-municipal-level statutes, voluntary agreements/regulations, common law, and treaties [13]. 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 [14]. Economic policies are also key, creating fiscal deterrents and/or incentives under which groundwater use decisions are made [15]. Environmental safeguards are another aspect, with requisites for data collection and monitoring as well as technical/environmental standards for well construction and pumping [16].

Researchers have long posited that the GWS governance framework may be unfit for purpose in high-groundwater-stress contexts of the GLB [17–22]. They concur on its inadequate consideration of sustainable yield, in particular its insufficient science-based guidelines and incentives promoting conservation and efficient uses that reflect the unique physical–environmental requirements of aquifers to maintain GWS. Growing cases of GWS decline across the basin highlight the need for binational-to-municipal levels of government within the hydrological boundaries of the GLB to provide policies and decision-making standards guiding management actions [23] that address human and climate drivers of GWS depletion [20]. It also presents an opportunity for the establishment of proactive multilevel governance measures designed to halt further proliferation of this problem. Retrospective analysis of historical governance characteristics has proven useful to deepen understanding of present-day policy gaps, and confirm inferences of why policies have led to current environmental outcomes [24]. 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 specter of groundwater insecurity deepening in vulnerable locales.

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 [25]. Per Figure 2, CPT operates by characterizing the intervening causal mechanism (n1 => n2 => 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." [26]. As such, the more empirical manifestations that are observed within the study period, the more confident researchers can be of the causal mechanism [27]. 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.

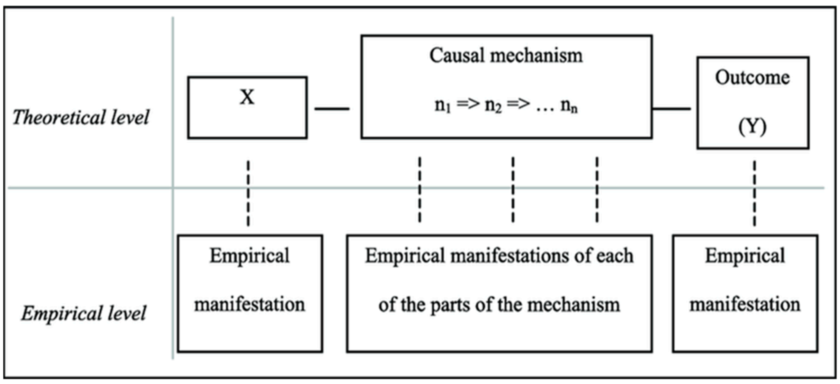

Figure 2. Elements of the causal process tracing method [27].

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 1.

Table 1. Causal process tracing application in research design.

CPT ELEMENT	APPLICATION IN RESEARCH
Causes (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, which have evolved over time, defining groundwater uses and environmental safeguards relevant to maintaining GWS.
Empirical manifestation/events (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 (=>)	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. In so doing, we describe the human and climate pressures driving GWS vulnerabilities, drawing from official government reports and published literature. We then 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 [28] and/or upwelling of deeper brines [29]; (ii) collapsing cavities in evaporates (e.g. gypsum) due to dissolution as pumping increases water velocity [30]; (iii) land subsidence due to over-pumping that reduces pore water pressure causing gradual lowering of land [30]; (iv) waning stream levels as baseflow declines [31]; (v) loss of groundwater-dependent ecosystems [32]; (vi) sustained decline of water table levels, defined as the upper limit of the underground where all interstices and voids are saturated with water [33]. Data on these indicators were sourced from desk studies of publicly available reports from peer-reviewed journals, GWS monitoring and governance institutions, and responses to our survey distributed from December 2018 to February 2019 to managers in these institutions. We received a 100% 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 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) [34]. From this, multilevel treaties, rules, and statutes (laws made by legislative bodies of governments at multiple levels) have evolved over the years [24]. As policies and standards component to the present-day GWS governance framework have not changed significantly since the 2020 USMCA and 2005 GLSWRA [22], the dates of the adoption of these binational agreements were considered appropriate for delimiting the study period. Data on the 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 [14,22].

Identification of empirical manifestations and causal linkages was made considering 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 or no pumping of aquifers and the total uptake of natural discharge [8,12,35]. Balancing these opposing governance strategies is largely science-based, as it considers the physical–environmental requirements of aquifers for maintaining GWS [35,36]. We applied the main concepts of sustainable aquifer yield theory 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; (iv) whether allowed and/or economically incentivized human uses disturbed the equilibrium required to sufficiently maintain GWS while avoiding unwanted outcomes. These evaluations were contextualized by the contemporaneous state of hydrogeological science at key governance milestones, given that the understanding of physical–environmental parameters to maintain GWS evolved over the study period.

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 to provide recommendations to address governance gaps.

3. Results

3.1. Outcomes (Y): The Emerging Problem of Groundwater Insecurity and Linked Governance Gaps

- Characterizing Sub-Watershed-Scale GWS Decline

GLB groundwater is mainly pumped from five principal aquifer systems: the Cambrian–Ordovician, Silurian–Devonian, Mississippian, and Pennsylvanian bedrock aquifers that are composed mainly of carbonates and sandstone, as well as the overlying, surficial aquifer system that is dominated by alluvium and glacial deposits [37]. Due to high permeability and effective porosity, the most productive aquifers are hosted in the unconsolidated sands and gravels of the surficial aquifer system [38] within which most wells are located. As GWS in surficial aquifers is prone to seasonal and climate fluctuations due to their relative shallowness, growing pumping rates often result in long-term groundwater decline, with occurrences being particularly reported in communities located in drought-prone locales and/or are heavily reliant on groundwater [39].

Occurrences of indicators of persistent GWS decline resulting from groundwater over-pumping have not yet been comprehensively documented in the GLB [32]. Based on available information, the impacts of over-pumping on GLB stream baseflow and groundwater-dependent ecosystems are poorly understood [13]. However, one well-documented case in Wisconsin linked excessive pumping to the drying of wetlands causing native habitat loss and invasive species spread [40].

Better documented are cases of long-term pumping reducing riverine baseflow given the interconnectedness of the Basin's surface water bodies with groundwater flow systems [41,42]. The Great Lakes are net groundwater receivers, with their tributaries gaining substantial volumes of water fluxes directly from the Basin's groundwater flow systems [42]. Groundwater contributes from 48% of streamflow in the Lake Erie Sub-Basin up to 79% in the Lake Michigan Sub-Basin [43]. Therefore, as over-pumping aquifers can reduce groundwater fluxes to surface water systems, it can diminish stream baseflow or, in extreme cases, reverse the normal flow of groundwater to surface water bodies. One of the most acute examples is occurring in aquifers supplying residents of the Chicago–Milwaukee metropolitan area and the Green Bay, Wisconsin, and Toledo, Ohio area. Here, long-term pumping has not only reduced stream baseflow but has reversed water flow from surface waters to aquifers [38].

As the Basin's hydrogeologic settings contain a substantial amount of glacial, unconsolidated deposits, some areas are susceptible to land subsidence due to groundwater decline caused by over-pumping [30]. Though not as prevalent in more drought-prone North American states/provinces, localized reports of land subsidence have been reported in Indiana, Wisconsin [44], and Michigan [45]. In regions where aquifers are hosted in karstic rock, sinkholes and cavity collapse can occur due to carbonate dissolution with pumping [46]. To illustrate, municipalities having high risks of gypsum cavity collapse linked to mining dewatering have been documented in Ontonagon, Houghton, Iosco, Keweenaw, Kent, Barry, Eaton, Calhoun, and Jackson counties in Michigan [47].

Upwelling of brines due to excessive mine dewatering has been reported in wells in the townships of Windsor and Romney, Ontario [13]. In Michigan, upwelling of brines due to long-term pumping for drinking water and agriculture has been well documented in Michigan's Lower Peninsula [48], as well as in Ottawa County that abuts northern Lake Michigan [49]. Arsenic concentrations exceeding the US Environmental Protection Agency's maximum contaminant level of 10 µg/L are often reported in well water in Southeast Michigan [50] in the counties of Huron, Tuscola, Sanilac, Lapeer, Genesee, Shiawassee, Livingston, Oakland, Macomb, and Washtenaw. These wells pump the Marshall Sandstone, hosted in the Mississippian basement aquifer system [37]. Relatedly, long-term pumping has caused drinking water of the straddling community of Waukesha, Wisconsin to be contaminated with radium, prompting its successful application for access to GLB water resources [51].

Responses to our survey indicated that persistent groundwater table decline occurs in aquifers supplying roughly 10% 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 (8) suburban counties including Genesee, Oakland, Macomb, Washtenaw, Wayne, St. Clair, Lapeer, and Monroe (communication from the Department of Environmental Quality on 5 December 2018). This has also been extensively documented in aquifers supplying Milwaukee and Chicago, including its eight (8) eastern suburban counties, as intense pumping beginning in 1864 caused groundwater table levels to decline by as much as 275 m by 1980 [52]. 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 [53]. These risks are particularly in droughts, the summer agricultural growing season, and periods of high municipal water demand used to supply the residential, industrial, and commercial sectors [54].

- 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 2005 GLSWRA. The binational agreement, aimed at sustaining the quantity of all GLB waters, generally prohibits withdrawals over 379,000 L/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 20 L 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 data base. 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/provinces responsibilities to regulate bulk water use; the most common regulation being Permit to Take Water (PTTW) programs.

Relevant economic policies include the 2020 USMCA, state/provincial PTTW 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 [55].

With identical policies guiding groundwater and surface water use, with high volumetric water use thresholds for bulk water definitions, binational-to-municipal levels of government often overlook fundamental physical–environmental differences between groundwater and surface water [7]. Sustainable aquifer yield considerations also appear to be largely ignored in federal and state/provincial governance of smaller volumes of GLB groundwater use [56]. 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 [34]. Instead, governmental oversight is typically limited to data-recording requirements and technical specifications for commissioning wells [14].

Economic policy tools generally encourage groundwater overuse, furthering groundwater insecurity risks in vulnerable locations [57]. 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 [14], and groundwater used for agriculture and firefighting are exempt from permits [58]. Finally, graduated block rates of municipal water supply tariffs can incentivize water wastage, as rates become progressively cheaper the more water is used [59].

3.2. Causal Mechanisms: Linking Historical GWS Governance to Current Outcomes

- Fundamental Legal and Scientific Principles Underpinning the Evolution of GWS Governance

In North America, controlling who has access to groundwater has historically been tied to land ownership and property rights [24]. This has its origins in the Absolute Ownership Rule of English common law [60] that allowed landowners to use groundwater below their property without limits or obligations to conserve the resource for neighbors or for future uses [61]. Court deliberations in the earliest documented application of the Absolute Ownership Rule—1843 Chasemore vs. Richards (1843-60 All E.R. 77, 81-82 H.L. 1859)—show that the court did not think it could 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." It is apparent that the Absolute Ownership Rule was originally devised based on the idea that groundwater quantity, flow rates, and flow directions were "unknowable", given the embryonic state of hydrogeological science at the time [62]. Later adopted in early North American governments, the Absolute Ownership Rule was modified to the Reasonable Use Rule, limiting groundwater uses to those done without waste or inhibiting the rights of adjacent property owners to access groundwater within their properties [63].

In multiple levels of GLB government, applying the Reasonable Use Rule to govern groundwater use has been nuanced by the Underground Stream Doctrine and the Public Trust Doctrine. The Underground Stream Doctrine interrelates surface water and groundwater rights of use, resulting in groundwater wells traditionally being treated as surface water diversions and groundwater flow considered "tributary" to GLB surface water [14]. Adding to this is the Public Trust Doctrine that originated from sixth century Roman civil law or "Institutes of Justinian", obliging governments to protect in perpetuity "things common to mankind—the air, running water, the sea, and consequently the shores of the sea." Used as the basis for environmental and natural resource protection laws, when the Public Trust Doctrine was adopted in the constitutions of newly formed North American states/provinces, governmental responsibilities to protect water resources originally extended only to surface water [63].

In this context, policies, standards, and court decisions governing GLB water use have traditionally prioritized safeguarding surface water quantities. Unless the purpose of groundwater protection has been closely tied to safeguarding surface water quantity for the greater public good, governmental oversight of groundwater use has been lacking, with groundwater use being traditionally treated as a private property rights issue [24]. Remaining largely unchanged over the years, these legal principles have carried through multilevel GWS governance, despite advances in scientific understanding of groundwater's physical–environmental sustainability requirements and its role in providing a range of vital environmental flows beyond baseflow to surface water bodies.

- The Evolution of Binational GWS Governance

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 prioritized maintaining surface water quantities [63]. Modern governance began with the 1909 Boundary Waters Treaty (1909 BWT) that banned large diversions of surface waters straddling the international border. Aiming to ensure equitable "domestic and sanitary uses, navigation uses, and uses for power and irrigation", it established the International Joint Commission (IJC). The IJC did not have a major GWS governance role until the 1988 Cabin Creek Coal Mine case, when its Water Use Reference was updated allowing investigation of GWS issues as a matter of practice [64].

The next significant binational agreement 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." However, its mandate was limited to the Great Lakes and all connected "rivers, ponds, lakes, streams and other watercourses.", reflecting the original interpretation of the Public Trust Doctrine by excluding groundwater from its purview.

Another important update was the 1985 Great Lakes Charter (1985 Charter). Established as a good faith agreement between the GLB governors and premiers, it is significant as it introduced many of the key standards and policies for the uses of "all GLB waters" still in place in today. It expanded GLC membership to include Canadian premiers, introduced the regional review process for making decisions on bulk water use and diversions, and most significantly, was the first binational agreement to include groundwater in its purview as a public trust responsibility [65]. Improving science–policy alignment, the 1985 Charter introduced volumetric limits to GLB water use to safeguard "nonrenewable" GLB water resources. It required regional review of bulk water uses, defined as any withdrawal exceeding 380,000 L/day in any 30-day average, and any new or increased diversion or consumption of GLB water exceeding 19 million liters per day in any 30-day period. It also initiated the Great Lakes St. Lawrence River Regional Water Use Database that was eventually established in 1988.

Despite these milestones, the 1985 Charter did not appear to consider sustainable aquifer yield in recommending policies and standards to govern groundwater use. Notwithstanding well-documented knowledge that aquifers can be depleted due to over-pumping since 1910 [62], the 1985 Charter did not reflect on groundwater's relative scarcity and lower replenishment rates compared with surface waters as it provided identical volumetric definitions and controls for bulk groundwater and surface water use. By stating its overall aim was to safeguard GLB surface waters, it invoked the Underground Stream Doctrine, considering groundwater flow systems as merely tributaries to surface water bodies, and interrelating the policies governing the uses of both resources. In so doing, it failed to keep pace with groundwater science that had advanced considerably from the 19th century in North America. By 1903, key hydrogeological concepts relevant to sustainable aquifer yield had been developed, including that environmental flows provided by groundwater were not just limited to surface water bodies, as well as the relationship between groundwater budgets and sustainable limits for consumptive uses and aquifer geometry and geological media [62]. Though the Regional Water Use Database has been providing yearly reports on GLB water withdrawals, consumption, and diversions, since its inception it has not had a specific data field for tracking water use from aquifers. This has made it difficult to garner consistent groundwater use data, an essential input for determining sustainable aquifer yield.

Since the 1985 Charter's original policy prescriptions remained largely unchanged in the intervening years, many of its original GWS governance gaps have carried through to the present day. 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, committing the GLB states/provinces to agree on policies to be included in laws within the next three (3) years. This was fulfilled when the 2005 GLSWRA was passed and subsequently integrated into current state/provincial laws governing GLB water use.

Sustainable aquifer yield considerations have also been absent from binational economic policies affecting GWS. Though they can be traced back to the 1855 Reciprocity Treaty, it was not until 1987 that the first such policy 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." Successive trade agreements have ignored the cumulative impacts the virtual groundwater trade can have over time on source aquifers and the environmental safeguards for maintaining GWS. Instead, these agreements have always included settlement mechanisms for trade disputes, opening the door to growing competition and conflicts between conservationists and industries drawn to the Basin by its cheap, clean, and abundant groundwater supply [66].

- The Evolution of Federal GWS Governance

Per the 1867 Canadian Constitution, the Canadian federal government has had a historically limited role controlling groundwater use, restricted to aquifers within international borders and those underlying railways, federal, and First Nations lands. It has been most involved in geological 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 [67]. The US federal government has also long facilitated similar hydrogeological research, founding the United States 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 [68]. As such, most GWS governance roles rest with the eight (8) GLB states and Ontario.

Despite the federal governments' long-standing facilitation of hydrogeological research, there is little evidence to suggest that sustainable aquifer yield considerations have been taken into account in successive court rulings or state/provincial laws and decision-making standards impacting GWS. Remaining mostly unchanged from its original 19th century legal doctrines that were based on 19th century scientific understanding of groundwater flow systems, the evolution of state/provincial GWS governance is evaluated below.

- The Evolution of State/Provincial GWS Governance

After agreeing on the 1956 Great Lakes Compact, GLB states/provinces adopted bulk water use and diversion counsels of successive binational agreements. In so doing, they followed the historical trend of overlooking sustainable aquifer yield requirements and favoring surface water preservation objectives. As such, the focus of this assessment is on the governance of smaller volumes of GLB groundwater use within the study period. This is because, despite much of the theoretical foundation and rudimentary groundwater quantification and modelling methodologies being established by 1940 [62], there has been considerable variation in the degree to which these policies and decision-making standards kept pace with these scientific advances and took sustainable yield considerations into account [69]. We also evaluate court rulings to resolve groundwater use conflicts during the study period. As the only state wholly within the Basin's boundaries, we focus analysis on Michigan's court decisions as its many landmark rulings demonstrate well how groundwater conflict resolution has been historically treated in case law.

I. Ontario

Ontario had some of the earliest policies in place impacting GWS in the study period. Its Ontario Water Resources Act (OWRA) mandated licensing and pumping rate data collection since 1961 [67]. A 1990 OWRA amendment introduced more stringent requirements for bulk water use than those of the 1985 Charter, requiring permits for taking over 50,000 L 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 USD 3000 for groundwater PTTWs issued in high-use regions and/or for water-bottling purposes (Section 34). The 2001 Ontario Municipal Act was the only GLB policy within the study period 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 considered temporal aspects impacting groundwater availability, setting progressive restrictions on water pumping corresponding to reducing levels of streamflow and/or precipitation in times of drought.

II. Pennsylvania

Far stricter than most GLB states/provinces, in Pennsylvania there has been longstanding consideration of the 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 GWS 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. The 1984 Safe Drinking Water Act appeared to consider sustainable aquifer yield by empowering municipalities to issue permits, at an annual fee capped at USD 500 for persons taking groundwater from publicly owned aquifers. It also required EIAs on aquifers as part of groundwater permit requests. Finally, 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.

III. Minnesota

Unlike Pennsylvania and Ontario, Minnesota has had far less consideration of sustainable aquifer yield requirements in its statutes and regulations impacting GWS. Instead, the state has had a tradition of having little to no regulations for the use of groundwater within private land, rather focusing on the protection of water within publicly owned lands. In 1897, Minnesota 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 water protections, which for the first time included groundwater, as 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 required for large-quantity uses of public waters as well as for the appropriation of public waters for agricultural, industrial, and commercial sectors. Yet, the permit fee structure remained the same for groundwater and surface water, thereby disregarding the differences in availability and recharge rates.

In 1976, the Public Waters Inventory Program was introduced to track water levels (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 aquifer recharge 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. Aiding the protection of groundwater within private and public lands, in response to the 1987–1989 drought, in 1990 the Minnesota Department of Natural Resources was mandated to develop a drought plan (Minnesota Statutes Section 103G.293). Still in use today, the resulting Minnesota Statewide Drought Plan consists of a set of prescribed local action responses to five different conditions/phases of climate (normal to extreme drought) [70].

IV. Wisconsin

Though Wisconsin has not had a long track record of laws reflecting sustainable aquifer yield considerations, and did not have regulations mandating reduced groundwater use during droughts over the study period, it has more recently developed one of the more comprehensive water use and aquifer protection policies of all GLB states/provinces. Its 1983 Comprehensive Groundwater Protection Act 410 (Chapter 160, Wisconsin Statutes) established the Groundwater Coordinating Council to assist state agencies' coordination of water conservation and provision of 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 USD 100 for both surface water and groundwater, economic incentives did not appear to consider their relative quantity and recharge disparities [71].

V. Indiana

Indiana's approach to GWS governance featured some of the least physical—environmental considerations for protecting GWS of all GLB states/provinces within the study period. Since 1860, Indiana has applied the "Reasonable/Beneficial Use system" to govern both surface water and groundwater uses [72]. 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." The first statute to provide some GWS protections was the 1985 Emergency Regulation of Ground Water Rights Act (IC 14-25-4). However, the law was concerned with protecting property rights to groundwater as it protected owners of small-capacity wells from the impacts of high-capacity wells if they significantly lower GWS levels within their properties. Still in use today, this law 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 groundwater (City of Valparaiso vs. 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. The 2003 Water Rights and Resources Act (Indiana Code 14-25-1(1)) furthered this approach to GWS governance. While it defined the types of water subject to government protection for the public welfare, it did not include groundwater. Similar to Minnesota, Indiana provided some recommendations to protect GWS in times of drought. Its 1994 Water Shortage Plan included environmental indicators of water shortages with corresponding groundwater use and management responses.

VI. Michigan

Prior to the passage of the 2005 GLSWRA, Michigan's statutes largely omitted standards to control groundwater use that reflected sustainable aquifer yield considerations [73]. In addition, most controls on groundwater use were set by the courts in settling groundwater use disputes, and rulings were primarily concerned with ensuring equitable access rights to groundwater within property limits. The earliest of these rulings was from the Michigan Supreme Court in the 1917 Schenk vs. City of Ann Arbor case (196 Mich 75, 163 NW 109), where it was found that the City of Ann Arbor did not have greater rights to withdraw groundwater for the provision of public water supply than a private landowner did. The court also ruled on another landmark case, Bernard vs. 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 vs. City of St. Louis, ruling in the Maerz vs. U.S. Steel Corporation case (116 Mich App 710).

Statutes that did cover GWS were first established in the late 1970s. Reflecting the Absolute Ownership Rule in stating that municipal governments had no authority to curb groundwater uses within private land, the 1978 Michigan Public Health Code (PA 368, MCL 333.1101 to 333.25211) indicated that "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. Michigan took its first steps towards conserving GWS based on sustainable aquifer yield considerations when it passed the 1994 Natural Resources and Environmental Protection Act 451 (Mich. Comp. Laws § 324.30106), requiring EIAs before granting permits to take groundwater. The 2003 Aquifer Protection and Dispute Resolution Act added further protections by setting withdrawal thresholds based on a regional groundwater model that can assess the degree to which aquifers are overexploited.

On economic policies impacting GWS during the study period, Michigan's court rulings have had implications on the extent to which free trade treaties could be applied to access groundwater prior to the 2020 USMCA. The Michigan Court of Appeals 2005 ruling on the Michigan Citizens for Water Conservation (MCWC) vs. Nestle Waters North America Incorporated (269 Mich. App. 25, 709 N.W.2d 174) is one of the most significant cases. Nestle previously purchased groundwater rights to a Sanctuary Springs property in Mecosta County, within which it established four high-capacity wells that pumped groundwater at a rate of 400 gallons per minute (576,000 gallons per day). The 1994 Natural Resources and Environmental Protection Act 451 was considered by the court in ruling for the MCWC, preventing 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 that Nestle's groundwater extraction was having on the ability of wetlands and watercourses to provide ecosystem services, including the reduction of their ability to provide fisheries habitat, water filtration, and to prevent erosion and flooding. The court ordered Nestle to cease operations pending determination of more sustainable groundwater withdrawal rate, allowing consideration of sustainable aquifer yield factors. It was not until after the study period, in the 2006 amendment to the 1994 Natural Resources and Environmental Protection Act 451, that any statutes were passed that regulated the removal of any quantity of GLB groundwater from an aquifer for free trade purposes [74].

VII. New York

Prior to the 2005 GLSWRA, New York statutes impacting GWS had minimal guidance that reflected sustainable aquifer yield considerations [75,76]. The first 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. The other significant measure during the study period was the 1988 Great Lakes Water Conservation and Management Act (NYS ECL § 15-1501 et seq.) that imposed EIA requirements on public water suppliers that withdrew large amounts of GLB water.

VIII. 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 [77]. 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 reaffirmed in the Bridgman vs. 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 permitted bulk groundwater pumping for domestic uses following its 1996 Rules and Regulations for the Allocation of Water from Lake Michigan.

IX. Ohio

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 [78]. 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. The court placed a duty on landowners to make 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.

4. Discussion

Results of our CPT analysis pinpoint the causes of gaps in the present day GWS governance framework that have led to emerging groundwater supply vulnerabilities in drought-prone and/or groundwater-dependent GLB communities. Referring to key aspects of CPT theory, below we outline the empirical manifestations and causal mechanisms—successive governance milestones/amendments and court rulings within the study period—that comprise the causal chain linking historical causes to present-day outcomes.

- Causes and Outcomes

The greatest strength of GWS governance over the years has been its facilitation of scientific research and data collection, which if applied, would have been relevant to devising groundwater use policies and decision-making standards based on sustainable aquifer yield. This is evidenced with federal governments' early establishment of the USGS and GSC, and their long-term collaboration with the states/provinces in aquifer mapping and monitoring GWS levels [67,68]. GLB states/provinces have fairly consistently required GWS-level data collection, and in some cases, have long required pumping-rate reporting, such as in Ontario, Pennsylvania, Minnesota, and Wisconsin. At the binational level, the 1956 Great Lakes Basin Compact was a key milestone as it initiated the whole-of-basin approach to GWS governance that has come to characterize successive agreements, catalyzing binational hydrological research and data sharing on GLB water resource use [65].

Data and science on aquifer geophysical parameters, flow rates, as well as technologies and methodologies for quantifying and simulating groundwater flow have been steadily improving over the study period. However, our findings suggest that although governments at multiple levels have facilitated much of this science that is relevant to sustainable aquifer yield, they insufficiently leveraged it to develop groundwater use and conservation rules over the study period. This feature is the root cause of present-day GWS governance weaknesses and groundwater decline outcomes.

CPT points to legal principles originating from 19th century court decisions and scientific understanding of groundwater flow systems as the fundamental cause of these outcomes. The oldest of these is the Absolute Ownership Rule. Court deliberations in its earliest documented application, the 1843 Chasemore vs. Richards ruling (1843-60 All E.R. 77, 81-82 H.L. 1859), shed light on the incipient state of hydrogeological science at the time that supported the creation of the legal concept that groundwater use could not be governed because its quantities and flow directions were "unknowable". From 1776 to 1865, the science of hydrogeology was characterized by slow growth in the understanding of underlying principles, especially in the Great Lakes region where springs were plentiful, not requiring early settlers to develop wells to access groundwater, or consider impacts of overuse [62]. Therefore, when the Reasonable Use Rule was later set to govern groundwater use, it was largely oriented towards protecting the rights of adjacent landowners to access groundwater within their property limits. Additionally, for much of the study period, GWS conservation for the greater public good was not prioritized, given the Public Trust Doctrine's incorporation into early state/provincial constitutions that regarded only surface water as a common, public resource. The Underground Stream Doctrine further entrenched this paradigm, as governments typically only stepped in to protect GWS for the purpose of safeguarding surface water.

It is from this scientific and legal basis that during the study period, successive GLB governments and courts at multiple levels largely failed to devise policies and standards for groundwater use and conservation based on sustainable aquifer yield. Carried through to the present day GWS governance framework, we outline the causal mechanisms culminating in current governance weaknesses and GWS decline outcomes.

- Empirical Manifestations and Causal Mechanisms

Focusing first on policies and decision-making standards controlling groundwater pumping, successive, multilevel statutes generally omitted specific, science-based measures based on sustainable aquifer yield during the study period. Echoing Underground Stream Doctrine paradigms, governments typically interrelated surface water and groundwater rights of use, not containing evidence of appreciation that there is five times more surface water than groundwater stored in the Basin [1]. With most governmental controls for groundwater use limited to bulk quantities, it is noteworthy that since being introduced in the 1985 Charter, the same high volumetric water use thresholds were used to define bulk surface water and groundwater, seeming to be better suited to surface water's greater availability and quicker recharge rates [79].

Another significant governance blind spot was the paucity of regulation of smaller quantities of groundwater uses. This is seen in groundwater exports from the Basin in containers 20 L or less being allowed in successive binational agreements leading to the 2005 GLSWRA; these agreements being purportedly aimed at preserving the quantity of all GLB waters. More evidence is that most GLB states, except for Ontario and Pennsylvania, did not have controls on smaller volumes of groundwater pumped within private land. Reflecting the legal principles of the Absolute Ownership Rule, governance focused rather on standards for well construction and pump installation. Groundwater pumping for firefighting and agriculture, regardless of the quantity, was also unregulated, despite the latter being the largest groundwater consuming sector in the Basin [57,59].

Past court rulings also provide more empirical manifestations that reflect 19th century scientific and legal principles. Rulings resolving groundwater use disputes seem to have been rather focused on ensuring equitable groundwater rights of landowners rather than preserving aquifer storage [80]. 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." In other instances, courts typically enforced the Reasonable Use Rule and/or Underground Stream Doctrine and applied jurisprudence on surface water, given its longer track record of case law, to resolve other groundwater use conflicts [72]. Notable examples are deliberations in the City of Valparaiso vs. Defler (694 N.E.2d 1177, 1180-82) ruling in Indiana and the Bernard vs. City of St. Louis ruling (220 Mich 159, 189 NW2d 891) in Michigan.

On GWS conservation, multilevel policies and decision-making standards had a mixed record on considering sustainable aquifer yield during the study period. Positive developments were the introduction of EIA requirements in PTTW decision-making standards for high-capacity wells beginning in the 1980s in some states/provinces, as well as their protection of waters needed for aquifer recharge. Moreover, with regard to the temporal dimension of safeguarding GWS, states/provinces introduced voluntary, judicious water use policies to protect GWS during droughts, with Pennsylvania and Ontario being the only jurisdictions where this was made mandatory during the study period.

Economic policy tools also reflected 19th century legal and scientific concepts, and typically appeared to disregard sustainable aquifer yield. 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 [63]. To illustrate, historically, fees for municipal water supply and state/provincial well permits and PTTWs have been low or nonexistent. Moreover, as these fees generally were not differentiated from the pricing structure for surface water, multiple levels of governments did not consider groundwater's relative scarcity and lower recharge rates, providing little economic incentives for reducing groundwater use.

- Causal Linkages

Legal principles originating from 19th century groundwater science do not appear to have persisted in successive court decisions, policies, and decision-making standards due to a lack of competence or understanding of hydrogeological science. Much of the theoretical, engineering, and methodological underpinnings needed to quantify groundwater and simulate its flow directions and rates were established since the 1940s [62], and GLB governments have demonstrated their ability to leverage these scientific advances towards safeguarding groundwater quality. GLB governments at multiple levels have had laws protecting groundwater quality since the 1970s that explicitly considered modern science on geophysical and environmental parameters [17]. Kickstarted with major environmental disasters such as the Love Canal catastrophe that leached hazardous chemicals into underlying groundwater 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 [81]. Since then, consecutive amendments of groundwater quality regulations have mostly kept pace with innovations in science, with there being some successes in improving groundwater quality across the GLB [82].

The above suggests that path dependency may be the likely rationale for GWS governance and groundwater quality governance having such contrasting outcomes. The phenomenon of governments starting down a particular track, making the costs of reversal or change extremely high to overcome [83], path dependency is the likely causal link through which GWS governance weaknesses were able to persist well into the present-day governance framework, inexorably contributing to growing water insecurity in high-stress locales. Hansen [84] 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.". As such, policies are inherently challenging to reform [85], even when suboptimal to address problems [86]. Often, policymakers typically must wait for critical junctures or exceptional opportunities to enact governance reform [87].

In this context, the evidence conveys that successive GLB governments have had little inducements to amend GWS governance as growing groundwater insecurities have been largely localized and location-specific problems [88]. This is compounded by GLB residents generally having low water risk literacy, lulled into the "myth of water abundance", relatively unaware of risks posed by droughts and rising uses [89,90]. With growing groundwater vulnerabilities not yet garnering widespread public attention, or becoming a Basin-scale problem, public pressure or significant inflection points have not yet demanded GWS governance reforms considering sustainable aquifer yield.

5. Conclusions and Recommendations

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% [5]. Currently, 10% of the US population and 40% of the Canadian population reside within the GLB [91], with some of the fastest growth in inland peri-urban communities. For many communities, groundwater is often the sole source of public water supply: e.g., almost half of Michigan residents and a third of Ohio residents depend on GLB groundwater for public water supply [92]. With industry increasingly being attracted to the Basin, drawn by clean waters and cheap water prices, these trends have already contributed a thirtyfold increase in regional groundwater withdrawal, currently estimated at 160,000 L/day [2]; as well as an overall 15% increase in groundwater consumption across the Basin, while surface water consumption decreased within the study period [93]. If left unchecked, these trends are likely to proliferate groundwater overuse, particularly in population growth and industrialized hotspots, raising the specter of groundwater insecurity deepening in high-stress locales.

To contend with rising GWS threats, our findings argue strongly in favor of reforms of policies and standards regulating groundwater pumping, use, and conservation. As demonstrated with improvements made with water quality governance due to public pressure, inflection points can make fundamental governance reforms possible [87]. Considering this, 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. Therefore, raising awareness on the increasing cases and socio-environmental drivers of GWS vulnerabilities across the Basin is key.

Secondly, we urge for groundwater use governance to keep pace with scientific findings of the twenty-first century. It is clear that the Absolute Ownership Rule that underpins the evolution of GWS governance was based on legal concepts predicated on 19th century science, as governments avoided the establishment of specific rules to govern the use of a resource they could not quantify or trace. Through path dependency, they instead applied rules originally devised and better suited to maintain surface water quantity, despite advances in science that increasingly recognized groundwater as quantifiable resources supporting vital environmental functions and economically valuable human uses. In so doing, GLB governments at multiple levels have not recognized that the original interpretation and establishment of these rules were very much a product of their time.

Since then, a great deal more knowledge and data on groundwater flow rates, directions, and quantities have been accrued as the hydrogeological scientific discipline matured. Twenty-first century innovations such as Big Data, GIS, remote sensing, and machine learning technologies to estimate aquifer geometry, quantify GWS, and model groundwater flow directions [94] carry the promise of faster, cheaper, and increasingly accurate estimations of the physical–environmental parameters of sustainable yield [95]. While the significant natural variation in aquifer physical–environmental settings would evidently impact planning needs and options to address highly localized to regional-scale GWS sustainability issues, by leveraging these innovations, more sustainable policies and decision-making standards to better sustain GWS may be created [96].

At the heart of GWS governance are its foundational legal doctrines and scientific assumptions. Courts and governments at multiple levels would need to make a definitive update of the Reasonable Use Rule relevant to the situational contexts of their GWS governance mandates. These considerations imply the abandoning the Underground Stream Doctrine in order to determine reasonable groundwater uses based on sustainable aquifer yield concepts. This contemplates (i) specification of volumetric thresholds for groundwater uses that avoid undesirable consequences on surface water bodies, aquifers, and dependent ecosystems in legal definitions; (ii) adding a temporal dimension to determining reasonable groundwater use, lowering use rates during droughts; (iii) considering the cumulative impacts of smaller-capacity wells over time [97], and (iv) differentiation of bulk water definitions for groundwater and surface water, with lower volumes set for the former given its relative scarcity and differing physical–environmental requirements of aquifers to maintain groundwater.

Restricting what is now considered "reasonable uses" of groundwater will likely require expansion of the Public Trust Doctrine [72]. However, applying public trust principles to govern groundwater use in the GLB has been rejected in the past due to fears over violating private property rights [98]. A 1983 California Supreme Court ruling (National Audubon Society vs. 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. By according public trust responsibilities to landowners, it effectively placed a duty on them to conserve groundwater below their lands.

Our third recommendation is to update economic policy tools to incentivize groundwater use efficiency. The structure of costs created by past GWS governance policies has resulted in groundwater being cheap and freely available to well owners, and insufficiently covering the cost of extraction and distribution of municipal water supply [59]. Regarding free trade agreements, these features have been embedded in the business models of industries attracted to the region [99]. While most GLB states/provinces 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, who since the 1990s has set higher PTTW pricing for withdrawing bulk groundwater than for 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, there has been a tradition of collaboration and cooperation across political jurisdictions and government levels. The region's governments have established enduring institutions and more recently, taken steps to enshrine policies into 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. With this trajectory, there can be some confidence in GLB continuing its transboundary governance evolution towards better science–policy alignment, to sustain "all waters" of the Basin, rising to the challenges of growing climate and growing human use stressors on vulnerable aquifers.

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