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Transboundary Aquifer Management Across the Americas: Hydro-Diplomacy as an Accelerator of Adaptive Groundwater Governance Amid Climate Change Challenges

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Abstract: The management of transboundary aquifers across the Americas faces significant challenges, especially as climate change and population growth intensify groundwater stress. Groundwater use has increased to support domestic, industrial, and agricultural demands but has been extracted through unregulated withdrawals, leading to the severe degradation of aquifer health and transboundary frictions. This study focuses on how hydro-diplomacy can accelerate the adaptive governance of shared groundwater resources in three key regions: Canada–USA, USA–Mexico, and Mexico–Guatemala–Belize. We utilized a mixed methodology by integrating a transect approach, borrowed from ecology, into the field of geopolitics. To compare the hydro-diplomatic relations and groundwater governance across a continental gradient in the Americas, we conducted a literature review and employed the TWINS conflict–cooperation matrix to evaluate governance frameworks and hydro-diplomatic interactions across time. Our findings demonstrate that hydro-diplomacy plays a pivotal role in expediting agreements, fostering transboundary data sharing, and supporting participatory governance models. In particular, the presence of supranational bodies such as the International Joint Commission (IJC) between Canada and the USA has been effective in maintaining long-term collaboration through social learning and technical cooperation. Meanwhile, in regions like Mexico–Guatemala–Belize, the absence of robust institutions has hindered progress, with limited financial and knowledge-sharing networks. This study highlights the need for improved cross-border cooperation mechanisms and the establishment of common monitoring protocols to better manage aquifer resources under the pressures of climate change. The results support the development of more adaptive transboundary groundwater management strategies aligned with Sustainable Development Goal (SDG) 6.5.2 and call for broader geopolitical cooperation to address the complexities of groundwater governance.

Keywords: hydro-diplomacy; groundwater governance; Americas; transboundary aquifers; SDG 6.5.2.; adaptive management; climate change

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1. Introduction

1.1. Transboundary Aquifers, Groundwater Management–Hydro-Diplomacy and Climate Change Challenges

Groundwater is a critical resource for society, as it provides drinking water and enables sanitation, irrigation, and industrial cooling across the Americas [1–6]. It also sustains ecological processes, such as feeding springs for wetlands sustenance [7–9]. The Americas'

dependency on well water has been evident for centuries. For this reason, groundwater quantity in North America has been a topic of high-level diplomatic conversations since 1909 [10] but effectively managed and safeguarded by Indigenous communities long before the establishment of formal transboundary committees [11]. In the Yucatán Peninsula, Mayan people mapped, stored, and distributed groundwater for crop growing, sacred rituals, and cement production. In doing so, they were very much aware of the distinct origin of their groundwater and constructed a complex society around the awareness that water harvesting—not just extracting—is essential to human subsistence [11]. However, 16th-century Spanish colonisation led to a gradual tightening of controls over the communal use of the liquid resource. Ownership over groundwater was claimed to ensure the conversion of local agricultural grounds to large-scale haciendas, which allegedly required the dismantling of Mayan institutions and integrated water management practices.

Fast forward to the last decade, the combination of climate change and population growth has been significantly degrading groundwater health [8,12–14]. Hydrogeologists have proven that aquifer storage is at a historical low [13,14], and the healthy pools still in existence have been increasingly affected by anthropogenic pollution [15,16]. There have been fundamental advancements in aquifer monitoring studies, which have been insightful in demonstrating the implications of aquifer pollution caused by uncontrolled—or loosely legislated—withdrawals [17,18]. Unlawful exploitation of aquifers particularly concerns the high probability of spreading pathogens in karst systems and toxic waste across shared aquifers due to the lack of inadequate precautions against external pollutants and debris infiltration [19,20]. When aquifers exceed safe toxicity levels, they cannot be tapped into, even if surface water is unavailable for human consumption. This phenomenon has already taken place in the Americas and has had stark implications for food production [6,21], human health [19], and geopolitical stability [22]. Hence, groundwater governance is essential to prevent pollution and overexploitation, to safeguard this slow-recharging common good [6,14].Indeed, along the American continent, several aquifers happen to be transboundary, calling for the collaborative monitoring and conservation of groundwater pools.

To ensure the implementation of just, adaptive and inclusive groundwater policies, it is imperative that neighbouring countries build fertile diplomatic relations [23]. Many studies have already proven that diminishing freshwater reserves are expected to play a significant role in the emergence of transboundary conflicts [24], suggesting the need for an urgent revision (or creation, in some cases) of common water management frameworks adapted to evolving environmental conditions. To date, studies conducted at Transboundary Freshwater Diplomacy Database [24] have assessed that—in most sampled cases—transboundary conflict between nations has often resulted in cooperative outcomes as opposed to violent conflict, which represents an encouraging symptom of the current diplomatic trajectory of nation states. Yet the interface between climate change and poor aquifer management has exposed key intersectional issues which have been challenging to unravel, which may increase the complexity of how cross-boundary water relations may unravel [25–27]. With higher uncertainty under increasing groundwater stress, conflict could to arise, underling the pivotal importance of developing the field of hydro diplomacy studies.

The first challenge is that the parameters of aquifer health can vary significantly within and across borders due to diverse geological and hydrological conditions that characterise the aquifers [28]. This variability makes establishing uniform monitoring standards and deriving accurate conclusions particularly challenging. Secondly, subterranean water is 'invisible', and so is the deterioration of its health due to climate change [13]. Hence, the social impact of aquifer depletion often becomes evident only after groundwater health falls below a critical threshold [29]. In such instances, it is too late to intervene, though prevention and governance bodies need to intervene through 'responsive' groundwater management—usually less effective and more time-consuming [1,4,30]. On a third note, groundwater is a continuously moving resource, the volume and health of which vary with regional precipitation patterns and local anthropogenic uses of water; thereby, specific

management solutions can only be coordinated through collective orchestration and intersectoral liaisons between upstream and downstream communities [31].

1.2. Addressing the Wicked Problem

Coordination of intentions, needs, and actions is a wicked problem due to the number of actors interacting in the water governance space. When stakeholders merge their understanding of the issue at stake, they carry political, economic, and racially charged legacies which inevitably define the trajectory of diplomatic relations [27,32–34]. Aquifer governance implies addressing power dimensions in the exchanges between bordering countries that draw from the same transboundary aquifer. In this respect, Zeitoun and colleagues [35] confronted hydro-hegemony, the transboundary water interaction analysis (TWINS), and the virtual water river frameworks against empirical evidence from case studies in implementing countries. The review showed that the degree of dependency on the transboundary water source of the communities involved, their economic capacity, and their de facto power in the extraction and management of the liquid resource altogether influence the achievement of transboundary groundwater governance arrangements [35,36].

For communities to establish successful transboundary water governance arrangements, Zeitoun et al. [35] further argue that water issues affecting communities living on a shared aquifer must be raised to the national political agenda of each country involved. Raising local demands to high-level negotiations by placing them on the national political agenda ensures the appropriate investment of resources of all participating countries where communities in need dwell [28]. Hence, it could be said that confrontation denoted by varying degrees of conflict may be beneficial—under specific conditions—to the ultimate achievement of inter-state technical interaction over groundwater matters.

Conflict, according to Kuzdas et al. [37], must be differentiated between overt conflicts—directly affecting the design process of groundwater arrangements—and frictions that remain collateral to the formal diplomatic process. This consideration is vital to separate contexts in which affected parties are involved in the design process (e.g., minimizing conflicts and maximizing inclusion), from those where marginalized people are not included in the design of the arrangement or do not have the power and alliances to bring the issues affecting them to the forefront. As reflected by Kuzdas et al. [37], those latent conflicts are inherent in the realm of water governance, and, in the absence of mitigating efforts, they can eventually escalate to manifest disputes (e.g., political, legal, or economic litigations), civic (e.g., including violence, threats of harm, non-peaceful protests, vandalism) and destabilization characterized by frequent violence, disregard for the law, prolonged periods of fear, or even the breakdown of governing institutions. Because conflict and cooperation may be initiated at any governance scale and by elected officials as well as non-governmental actors (e.g., non-state actors, criminal organizations, Indigenous groups, civil organizations, etc.), we decided to explore the dimensions of 'conflict and cooperation' through the lens of various entities in the actor network.

Another consideration by Zeitoun et al. [35] refers to the historical context of diplomatic relations involving participating countries and the appreciation of local cultural and historical processes in shaping transboundary groundwater agreements. The historical evolution of relationships among societies inhabiting current watersheds can contribute to the emergence of transboundary governance of aquifers. An example is the Rhine River basin governance [38], which evolved over centuries of cultural and political exchanges. Here, inter-state interactions began during Roman times, a period during which extraction rules were applied to upstream and downstream communities. These cooperative dynamics, polished throughout the centuries, ultimately led to the adoption of the current European Union Water Framework Directive.

As conflict and cooperation for the governance of common resources may occur across scales, we assume that the existence of cooperative processes at the national scale may obscure the presence of friction in sub-national management friction in sub-national management bodies. Hence, we drew from Ostrom's elaborations [39], from water dis-

putes studies, and from peace studies [37,40], to challenge a stylized relationship between transboundary water governance arrangements and conflicts/cooperation outcomes.

1.3. Objectives

In the case of transboundary groundwater bodies, significant uncertainties regarding water health dynamics across space and time, especially in climate change [41], impose an even larger challenge to the efforts of state and local-level institutions that engage in the design of governance arrangements. As observed in transboundary water governance litigations, the existence of epistemic communities can increase available scientific knowledge and support processes to build shared understanding and initiate governance arrangements, despite deep uncertainties about groundwater dynamics [24]. The intersection between resource dependency, economic capacity, and executive power specifically affects groundwater management practices and collaboration in a transboundary watershed [21]. In this study, we examine the evolution of three critical dimensions within the realm of hydro-politics to illuminate the development of diplomatic alignment over time. Our analysis focuses on groundwater health management, specifically on quality, using three American case studies to explore how diplomatic strategies and policies have adapted to address groundwater challenges. Our research objectives also align with the work of Zeitoun et al. [35] and Mirumachi et al. [28], whereby conflict and cooperation are seen as non-exclusive variables in the development of transboundary water governance and may exist contemporarily in the same region. This interpretation reflects a more realistic profile of the current dynamics of groundwater negotiations, allowing for observing the evolution of groundwater agreements across different scales, time periods, and actor networks.

Furthermore, datasets can promote common understandings amongst bordering communities and enhance relations, as they may be used as a power tool to outplay other less knowledgeable parties by developing alternative discourses and narratives [22]. Drawing from [38], this study investigates potentially similar cultural exchanges in the chosen case study areas.

Also, managing transboundary groundwaters necessitates supporting intersectoral dialogues and assessments, applying integrated approaches, and understanding socio-ecological dynamics. This is why we adopted hydro-diplomacy principles as a conceptual perspective to guide our analysis. The framework is embedded in the field of foreign relations. It involves studying how diplomatic instruments can be applied to the domain of shared waters to enhance cooperation over conflict [42]. The concept has been circulating for several years but has not been explicitly applied to a comparative study investigating multi-scale groundwater interactions in the American context. Through the consultation of published works by Varady [43], Wilder [44], and Pétré at al. [45], we witnessed the operationalization of the analysis presented in Mirumachi et al. [46]. We developed a guiding research question for our case study area: *"Under which conditions can hydro-diplomacy be best utilized to expedite the creation of adaptive groundwater management agreements under the challenging socio-ecological circumstances posed by climate change across the American continent?"*.

In the context of the above-stated arguments, we performed a scoping review to grasp the depth and extent of the existing peer-reviewed literature concerning comparative hydro-diplomacy studies across the American continent. Informed by the works of hydro-diplomacy theorists [43,47], we consulted articles from the field of hydro-hegemony studies to understand upstream/downstream dynamics [27], on Indigenous inclusion in policymaking processes [43], on indicator 6.5.2. of the SDG framework [48] to set the ideal goal for countries to reach following the full implementation of hydro-diplomatic practices. Additionally, we consulted the work of Ostrom [39] to explore the setup of transboundary institutions that manage shared resources and Mirumachi et al. [46] on frameworks for monitoring conflict and cooperation across nations.

2. Methods

We answered the main research question by first performing a systematic analysis along the case study transect to characterize the status of adaptive groundwater management across the case study areas. Later, we analysed hydro-diplomacy trajectories in the exact locations. We used a mixed methods approach divided into 4 phases (Figure 1). Each phase had to be completed before the team moved on to the next segment, as the output of one research round represented the input to the following one. In Figure 1, overlapping clusters describe the interconnected nature of the research phases. Different colors show the diverse objective and format of each analytical exercise. We performed the scoping exercise to understand the geological and hydrological characteristics of various transboundary aquifers along the American continent. We selected the smallest (i.e., km^2) and least studied aquifers (i.e., number of mentions in peer-reviewed works) if sufficient data were available describing their hydrological cycles, climate specifications, topography, pollution status, topography, and history of diplomatic exchanges.

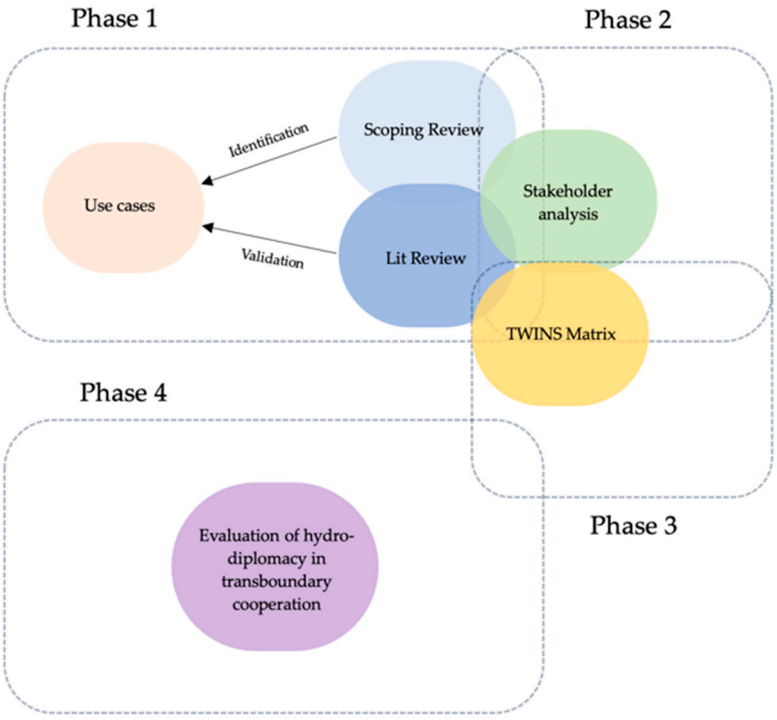

Figure 1. Methodological framework in 4 phases. Source: authors.

2.1. Key Aspects of This Methodological Approach

(a) Transect and case study approach

Our research borrowed a transect approach from the field of ecology [49] to compare the development history of hydro-diplomatic relations across a continental gradient (Figure 2). We analyzed the governmental, financial, and knowledge production structure of institutions, including First Nations, Native American, and Native People, in water governance, the historical legacy, and the specific objectives and mandates of the institutions tasked with managing aquifers in the different regions. For each selected area, we mapped the evolution of institutional arrangements using secondary data, including policy documents, agreements, treaties, press conference transcripts, and reports. We could compare multiple stakeholder groups in the system, their contributions to policy development, their perceived legitimacy, and their demands compared to the historical development of the hydro-diplomatic relations mentioned. We built on previous conflict and cooperation assessment frameworks applied to transboundary water governance assessment [22,27,46] and assessed conflict and cooperation trends at multiple scales of analysis focusing on

nation-to-nation exchanges and sub-national actor networks. From an ecological perspective, we analyzed the aquifers systematically, regarding precipitations, soil properties, polluting elements, and topographic characteristics per each case study area to compare major differences and similarities (Appendix A, Table A1).

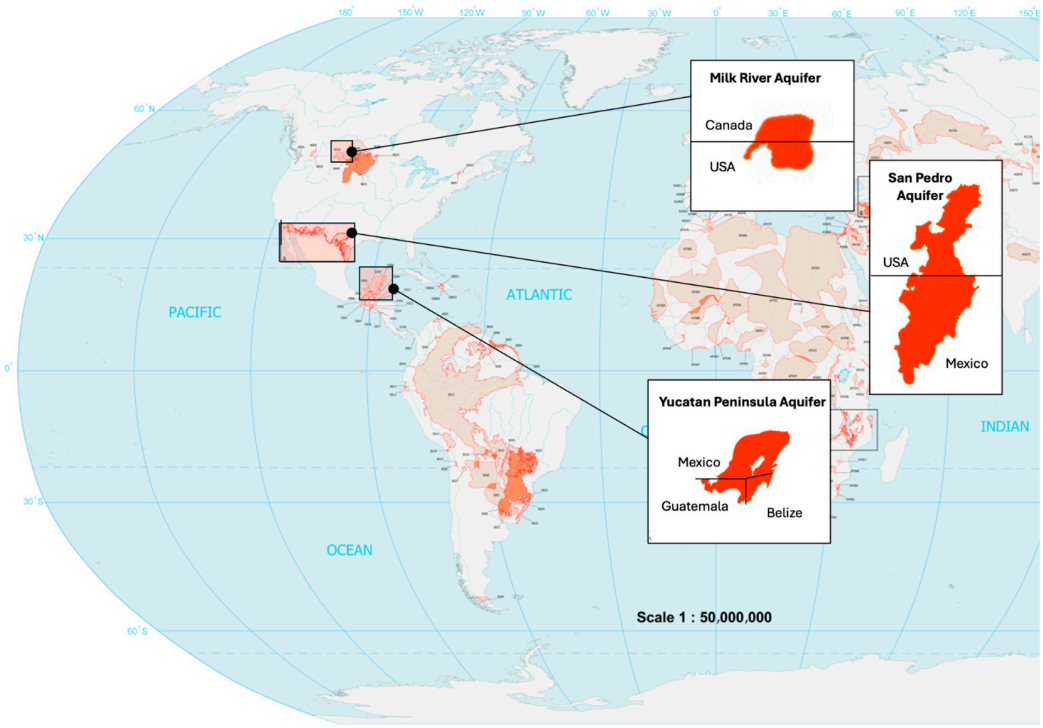

Figure 2. Map of transboundary aquifers across at a global scale [8], with zoom on the specific aquifers considered in the American Continent. Adapted by G.I.R.

(b) Document analysis for case study assessment

We performed a deep literature review to collect relevant demographic information about the three chosen case studies (see Appendix A, Table A2). The collected data informed our qualitative analysis of the institutional structures and participation in management bodies, thereby allowing us to assess whether the current practices of hydro-diplomacy are inclusive and effective in promoting sustainable and cooperative management of shared water resources. The demographic information we collected through a deep literature review was crucial to understanding how hydro-diplomacy contributes to creating dynamic regional cooperation between nations and non-state actors and to what extent Indigenous and epistemic communities' knowledge is considered in these diplomatic efforts. By analyzing the cultural diversity and the inclusion of indigenous groups within Western transboundary institutions, we gained valuable insights into how diverse stakeholders are integrated into decision-making processes. This demographic data allowed us to assess the extent to which Indigenous and marginalized communities' traditional management practices are respected and incorporated across the four success indicators outlined in Table A3. By understanding the institutional structure and power dynamics within these management bodies, we could better evaluate the role of hydro-diplomacy in fostering cooperation. The qualitative analysis of grey literature and peer-reviewed works further enriched our understanding of the underlying narratives and power structures that influence regional cooperation, ultimately helping us determine how hydro-diplomacy can enhance collaboration among diverse actors in the context of climate-impacted transboundary aquifers.

We also used the literature review to collect salient information about the historical development of diplomacy in the aquifers, the financial exchanges, institutional developments, the establishment of governance bodies, and the role of civil society in the watersheds. The

categories were defined by Indicator 6.3.2. [48], which provided a reference for monitoring progress in transboundary cooperation. During the review, we selected treaties and agreements that mentioned groundwater health, where possible. In some cases, we retained data only on water management, either because published works available to us did not address the matter of groundwater health or because the issue had not been placed on the political agenda in the case study area analyzed. Finally, we performed a validation of the choice of our case studies, confronting the content of the mined text with the "hypothetical mechanisms that can make for "good and ideal" hydro-diplomacy" (Table 1). If we could find at least four points out of the nine mentioned in Ostrom [39], we kept the case study as part of the analysis.

Table 1. Hypothetical mechanisms that can make for "good and ideal" hydro-diplomacy be the best way forward to manage transboundary groundwater sustainably [39], compared to the performance of 3 case study transects.

	Ostrom Principles	MRTA	SPTA	YPA
1.	Interdependencies of groundwater resources across political borders.	✓	✓	✓
2.	Regional cooperation and fostering frameworks and platforms that facilitate dialogue and collaboration among countries sharing transboundary aquifers or groundwater basins. Establishing regional agreements and institutions can promote information sharing, joint monitoring, and the development of common management strategies.	✓	✓	X
3.	Embrace changing geopolitical realities and evolving hydrological conditions while recognizing the need for flexible governance structures that can respond to emerging challenges, such as population growth, climate change impacts, and changing water demand-supply dynamics.	✓	X	X
4.	Balancing Sovereignty and diplomacy is addressing the balance between national interest and shared regional responsibility in managing cross-border groundwater resources via developing mechanisms that respect the sovereignty of individual countries while fostering cooperative frameworks to ensure sustainable and equitable use of shared resources.	✓	✓	✓
5.	Boost stakeholder engagement, including that of governments, local communities, academia, and civil society, in the decision-making process and encouraging participatory approaches to ensure that diverse perspectives and interests are considered, encouraging ownership and cooperation among stakeholders.	✓	X	X
6.	Assessment of existing legal and institutional frameworks that establish transparent processes for cross-border groundwater governance. And agreements, protocols, and mechanisms that address resolving disputes, promotion of address resolving disputes, promoting sharing benefits, and equitable access to groundwater resources.	✓	✓	X
7.	Point data collection, monitoring, and sharing to enhance transparency, understanding, and informed decision-making with this, common standard protocols for data collection, sharing, and analysis should be established to support collaborative management of groundwater resources.	✓	✓	X
8.	Securing adequate financial resources and investment in capacity-building initiatives to strengthen the technical and institutional capacities of countries involved in regional groundwater governance.	✓	X	X
9.	Supporting knowledge exchange, training programs, and technical assistance to enhance expertise in groundwater management and addressing the governance of these resources in new geopolitical realities requires robust frameworks that promote regional cooperation and inclusive management approaches.	✓	✓	X

(c) Stakeholder analysis

Based on the mix of scientific and grey literature mentioned in the previous sections [50], we began to create a formal stakeholder analysis of relevant actors living on or active in the selected aquifer. We first mapped out general groups involved in the socio-political and economic endeavors of the aquifer, classifying them by 'group types' (e.g., indigenous groups in the U.S., scientists in Guatemala). The number of mentions in the literature reviewed granted them a place in the initial pool of stakeholders analyzed. Later, following a more detailed literature review, we organized them in the final stakeholder

overview according to the four indicators that are part of Indicator 6.5.2. ([48] Appendix A, Table A3).

2.2. Two Other Dimensions of the Assessment

2.2.1. TWINS Matrix Analysis to Understand Power in Transboundary Water Relations

Throughout our scoping review, we focused on using the TWINS matrix to track the historical progress of transboundary relations in our selected case study areas. Our approach involved observing the evolution of geopolitical relations over time [46], keeping in mind two assumptions: (a) cooperation and conflict coexist in a real-life setting; (b) a shaping force of cooperation and conflict across basins is climate change. We first created a timeline of selected key historical events that significantly impacted groundwater governance, such as treaties, accords, and periods of social turmoil, for each region (see Appendix A, Figure A1). We then inserted each event in a specific TWINS matrix cell, after defining its positioning (i.e., level of conflict, cooperation and robustness of political economy) through the output of our literature review. The matrix helped us map the politicization of local groundwater issues within each nation, revealing trends which could be compared with the conclusions found in Zeitoun [35], Schmeier [42], and Mirumachi et al. [46]. Finally, inspired by Vitale ([25], we created a visual representation of trends in conflict, cooperation, and robustness of political economy per each case study area (Figures 3–5). To do so, we generated a 3D histogram in RStudio to describe two trends. On the x-axis, y-axis, and z-axis, we observe the evolution of diplomatic relations towards more cooperative or conflictual trends, under changing degrees of robustness of the political economy. The bottom section of the image illustrates the dates in which the ratification treaties or accords, and periods of social turmoil, took place. The objective is to help the reader understand the temporal boundaries of the diplomatic evolutions, as some had more setbacks than others through the years.

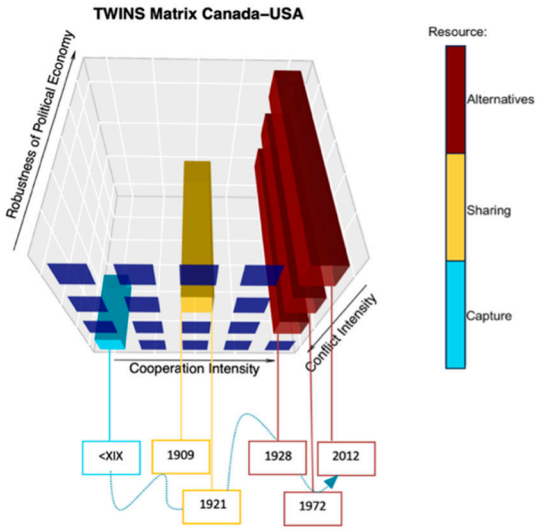

Figure 3. TWINS Analysis Canada–USA. Categories along the cooperation intensity axis (from left = lowest, to right = highest): confrontation of issue, ad hoc, technical, risk averting, risk taking. Categories along the Conflict Intensity axis (from front = lowest, to back = highest): violized, securitized/opportunized, politicized, non-politicized. Categories along the Robustness of Political Economy axis (from bottom = lowest, to top = highest): capture (in blue), sharing (in yellow) and alternatives (in red). G.I.R. adaptation from Mirumachi et al. [46].

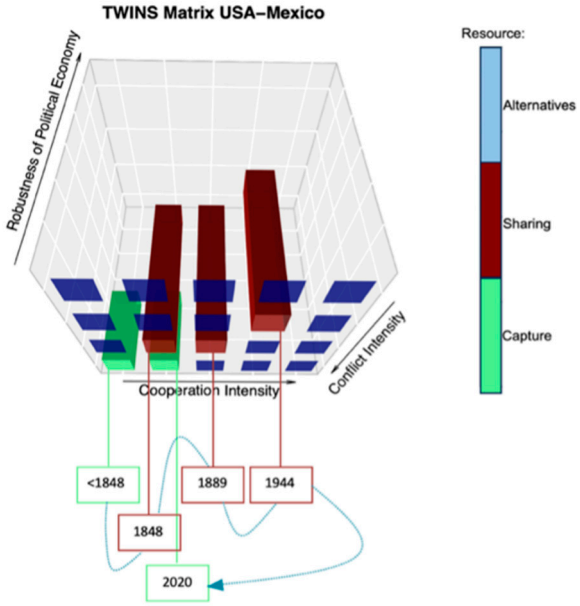

Figure 4. TWINS Analysis USA–Mexico. Categories along the cooperation intensity axis (from left = lowest, to right = highest): confrontation of issue, ad hoc, technical, risk averting, risk taking. Categories along the Conflict Intensity axis (from front = lowest, to back = highest): violized, securitized/opportunized, politicized, non-politicized. Categories along the Robustness of Political Economy axis (from bottom = lowest, to top = highest): capture (in green), sharing (in red) and alternatives (in blue). G.I.R. adaptation from Mirumachi et al. [46].

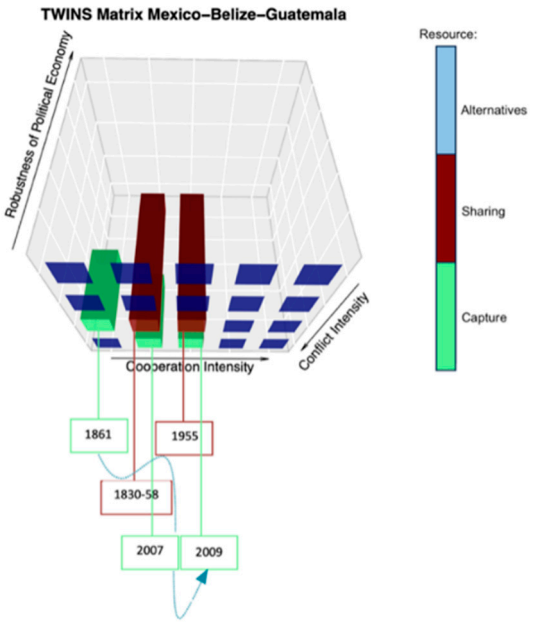

Figure 5. TWINS Analysis Mexico–Belize–Guatemala. Categories along the cooperation intensity axis (from left = lowest, to right = highest): confrontation of issue, ad hoc, technical, risk averting, risk taking. Categories along the Conflict Intensity axis (from front = lowest, to back = highest): violized, securitized/opportunized, politicized, non-politicized. Categories along the Robustness of Political Economy axis (from bottom = lowest, to top = highest): capture (in green), sharing (in red) and alternatives (in blue). G.I.R. adaptation from Mirumachi et al. [46].

2.2.2. Evaluating Hydro-Diplomacy for the Development of Transboundary Cooperation

Based on the literature review and TWINS matrix analysis, we evaluated the role of hydro-diplomacy in shaping transboundary and cooperative exchange over groundwater

across the years through a qualitative assessment. In the use cases in which the orchestration of efforts resulted in a success story—namely, all four SDG 6 indicators were positively measured—we studied the socio-ecological conditions that preceded and influenced the status quo. We performed the same exercise on the regions in SDG 6 indicators, which did not deliver positive results. By comparing the output of the two scenarios against the "Hypothetical mechanisms that can make for good and ideal hydro-diplomacy" [39], we assessed, qualitatively and systematically, which components could facilitate the integration of positive hydro-diplomacy outcomes in a specific region, considering social, economic, and cultural traits shaping power and policymaking.

3. Results

3.1. Main Aspects in Stakeholder Analysis and Transboundary Arrangements for Groundwater Management

On the Canada–US border (*North–North case*), many sources highlighted the pivotal role of the International Joint Commission (IJC) in the orchestration of activities across all four indicators in the MRTA [51]. The IJC represents the only supranational joint body present across the American transect. The officials on the advisory and executive boards of the organization are equally selected from the USA and Canada and possess equal mandates and signatory authority [52]. The initiatives of the IJC were most effective in administering nation-to-nation relations, especially about the financing of infrastructure for which diplomatic trust, strong political will, institutional safeguards (e.g., treaties, formal agreements…), and adequate agenda setting for long-term goal achievement are essential [52,53]. Multi-scalar governance interactions were noted, especially within knowledge production, whereby IJC officers had the mandate to convene a diverse array of professionals to deliver a groundwater management knowledge package founded in science. The group involved stakeholders holding executive power (mayors, provincial officials), civil society representatives (residents, Indigenous groups, associations), and technical advisors (hydrologists, engineers) [43].

On the Mexican front (*North-Meso and Meso-South focus regions*), we found that the national agency CONAGUA and the International Boundary Water Commission (IBWC) were tasked with ensuring the implementation of engineering projects. Differently from the MRTA case study, knowledge production in the San Pedro Aquifer (SPA) is initiated at the sub-national level and sustained by bilateral exchanges between universities and research centers, as opposed to multilateral interactions administered by the IJC [54]. Specifically, the literature suggests that knowledge production begins with a unilateral initiative and is then merged into multi-/bilateral exchanges at a later stage of development.

In the *Meso-South case* study, one joint body administers a transboundary orchestrating institution for resource management: the CILA Mexico–Guatemala and the CILA Mexico–Belize commissions. The commission's joint annual reports refer to boundary work without any reference to the management plans for transboundary rivers or aquifers, and groundwater resources are not mentioned. As mentioned, the CILA in both countries has focused on working on some infrastructure to maintain the borders between the countries and minor works in the river. In this case, the underperformance of the transboundary joint bodies stands out when compared to the influential joint bodies in the North–North scenario or to established bodies like the International Commission for the Protection of the Danube River (ICPDR). Other regional experiences, such as the Guarani aquifer, show better organization and a more established joint body despite weaknesses and constraints. Here, knowledge production is led by multilateral agencies (UNESCO-OAS), primarily through the ISARM Americas program. This initiative involved four regional ISARM networks of experts to identify, map, and manage transboundary aquifers (ISARM-Europe, ISARM-Americas, ISARM-Asia, and ISARM-Africa). Yet, there is no evidence that Mexico, Belize, and Guatemala used the insights from this experience to progress towards a trinational transboundary groundwater governance or to improve collaborative knowledge creation. National efforts to promote aquifer-related knowledge are only visible in Mexico.

However, the main emphasis of these initiatives is on the Mexican side, with CONAGUA at the forefront of driving initiatives to raise awareness about the significance and current state of national aquifers. No comparable organizations or initiatives in Guatemala and Belize focused on gathering information about their shared aquifers.

Two Key Observations

(a) *Financial contributions*: In the North–North case study, the US federal government allocated the most significant financial injections towards implementing management frameworks, increasing the capacity of dispatched officials and technicians to develop transboundary engineering projects. The literature underlined Canada's contributions to more diverse sub-national issues. The country directed more limited cash flows to projects at the regional level, focusing primarily on monitoring existing infrastructure. The unique trait of the IJC funding agreement between the two countries—which applies to the MRTA—is the existence of a transboundary pool of resources generally administered by the IJC. The vertical distribution of financial commitments in the North–North case study differs from the North-Meso use case, where—according to the reviewed literature—the US and Mexico unilaterally contribute national funds to groundwater management projects. In this focus region, it remains unknown which specific projects are being implemented due to limited public disclosure of technical briefs on transboundary groundwater projects. The mechanisms of interaction between the two countries, with specific reference to the adaptation of governance to climate impacts, also remain unclear.
We found that the evidence of cross-border collaboration from the financial perspective between Mexico, Guatemala, and Belize is largely lacking. Also, transboundary financial support for engineering and technology in the Meso-South case is inadequate and limited. Also, there is no evidence of cross-border financial commitment. CILA Mexico has led the financial efforts, but these investments have been focused on land and water boundaries. From the minutes' review, there is no mention of financial commitment or support for aquifer governance. The limited financial resources in the Meso-South case starkly contrast with the significant financial investment in the North–North.

(b) *Networks and actors*: This study identified a significant degree of actor diversity in the North–North case study at the supranational level. For this matter, many sources comment on integrating First Nation representatives into the advisory teams of the IJC, supported by high scores in Indicators 1 and 2 [43,52]. However, less cultural heterogeneity is found in the executive branches of the organization, as the Accredited Officers of the Milk River watershed do not include a First Nation delegate on the Canadian side, nor a Native American representative on the USA branch. A similar pattern emerges when exploring executive board membership at increasingly more minor scales of governance (Appendix A, Table A3). As jurisdictions shrink, the cultural homogeneity within governance clusters increases, and indigenous representatives are outnumbered by non-indigenous citizens (Appendix A, Table A3). A similar phenomenon seems to occur in NSA networks and non-governmental conservation groups, whereby clusters arguably do not count Indigenous representatives in their list of members [55]. Comparatively, the review of the minutes of the meetings held between the CILA Mexico–Guatemala and Mexico–Belize commissions illustrates no mention of Indigenous background amongst the actors participating in the discussions (Appendix A, Table A3). As per agents of knowledge production, members involved in aquifer management in the Meso-South case study act top-down from the national level, leaving minimal space for integrating local knowledge and demands.

The lack of transboundary state and non-state actor networks in the southern border region starkly contrasts the more developed networks observed in North–North cases. In the latter, numerous non-state-actor networks are actively engaged in transboundary management, encompassing a variety of actor types and scales. This disparity underscores

the need for enhanced collaboration and engagement among stakeholders in the southern border area to effectively address shared water resource challenges.

3.2. Main Findings from the TWINS Matrix Analysis

(a) ***Insights from the Milk River Transboundary Aquifer***

Along the Canada–USA border, successful transboundary water management was achieved through the iterative and decades-long process of experiencing and addressing "periods of interaction and non-interaction" [46]. The cross-border diplomatic interactions in the MRTA were initiated in 1889 in response to violent conflict over water allocation, which emerged in adjacent farmlands. Following the event, cooperation intensity in the region increased in a short period, developing from 'violized' conflict into 'technical' collaboration [46]. Moreover, conflict eradication has had slow development trends. Namely, as cooperation intensified at the national level, frictions at the sub-national scale still existed. This was especially true because of anthropogenic and natural interruptions to the access to water sources. Applying a multi-scale perspective on the politicization of water issues across levels of governance demonstrate no significant vulnerability of the transboundary governance infrastructure to local and regional turbulence.

We could say that the climate impacts have positively affected hydro-diplomatic relations. The North American transboundary relations, which had already shifted from debating matters of 'resource capture' to 'resource sharing', have entered the third tier of 'resource alternatives'– the highest along the 'robustness of political economy' axis. The diplomatic and climatic evolution in the North–North case study area demonstrates the pivotal role of transboundary epistemic communities, shared financial networks, and participative processes. These factors, operating amidst the challenges of deteriorating water health, have fostered sustainable water governance and contributed significantly to maintaining geopolitical stability throughout the twentieth century.

(b) ***Relapsing cooperation trends on the San Pedro Transboundary Aquifer***

The Guadalupe-Hidalgo Treaty ratified in 1848 marked the end of the Mexico–USA war, an armed territorial dispute during which the Rio Grande and the Colorado River, formally Mexican water bodies, were exploited for irrigation by the North American farming industry and weaponized during the nation-to-nation peace negotiations. From a conceptual standpoint, the treaty began a (slow) transition from 'violized' transboundary relations to 'ad hoc' collaboration, which perdured for over 50 years. The technical complexity of the transboundary agreements, which gradually came into being, spurred the shift from 'technical' to 'risk averting' collaboration between the USA and Mexico, demonstrating a stable progression in hydro-diplomatic relations at the national level, despite local turmoil over groundwater matters. Finally, the literature relative to the Meso-South case study was not sufficiently specific for the research team to observe multi-scalar interactions in the targeted location.

The North-Meso case study revealed different trends regarding the intersection between governance and climate. Frictions due to climate-induced water stress arose in 2020 and ultimately fractured the stability of existing US–Mexico institutional liaisons. This event pushed the positioning of the North-Meso case study back to a state of 'ad hoc' cooperation in the context of a 'securitized' use of water. Also, on the z-axis, the threshold regressed from a state of 'resource sharing' to one of 'resource capture'. However, studies performed in this region [24] described growing concerns over water security as having enhanced the frequency of transboundary exchanges. This suggests the potential for strengthening the political economy under conditions of climate change onset, as per the case of the MRTA. From the standpoint of financial contributions, the US federal government has committed USD 50 million to the TAAP fund for the assessment of three priority aquifer systems, which included the San Pedro aquifer. The financial injection was directed to the bi-national project, which inherently legitimized and reinforced hydro-diplomatic relations between the US and Mexico.

(c) ***Latent conflict in the Yucatan Peninsula Transboundary Aquifer***

The TWINS Matrix analysis offered a perspective on the non-linear diplomatic progression on the Meso-South border. This case study appeared to differ from the temporal alternation of cooperation found in the other two case studies along the transect. Although Mexico, Guatemala, and Belize have not formally engaged in open armed conflicts over matters of groundwater allocation, relations between the countries show tensions, nuisances, and non-overt—yet existing—disputes [56]. Disagreements often relapse on the specific segment of the Mexico–Guatemala border. Here, conflict has been triggered by water distribution matters, but—to date—hydro-diplomatic exchanges have not clarified shared responsibilities nor spurred ad hoc/technical' collaboration. When observing the governance–climate interplay, the collaboration over technical knowledge-sharing and financial cooperation to implement climate adaptation solutions has been insufficient. The central governance body (CILA) could have the mandate to orchestrate complex transboundary water management issues under changing climate standards. However, there have been minimal attempts to reach across the borders to install collaborative practices.

4. Discussion

Our research shows the development trajectory of hydro-diplomacy along a continuum of cases with diverse historical transboundary relations and development trajectories along a continental transect. We illustrate the conditions that facilitate or hamper hydro-diplomacy efforts that can enable adaptive groundwater management practices in a transboundary aquifer. Firstly, we innovatively use a transect approach borrowed from the field of environmental ecology to incorporate a new continental perspective in comparative policy studies. We think of the Americas in a territorial continuum, rather than being defined by Westphalian borders, mirroring the transboundary nature of aquifers. Secondly, in alignment with Mirumachi et al. [46]. we understand conflict and cooperation to be able to take place simultaneously within the same nation, depending on the granularity of one's study. Hence, we expand the definition of diplomatic relations beyond the traditional state-to-state interaction and explore—where possible—different types of hydro-diplomacy agents (i.e., NSAs) and dynamics.

4.1. First Transect: North–North Case Study

The Milk River Transboundary Aquifer case study was highly performant across all four indicators used in the analysis. We concluded that the results are linked to the active involvement of the IJC in matters related to groundwater health in Canada and the USA. One of the unique traits of the successful orchestrating body is its thorough development since its formation. Founded at the beginning of the XIX century, the transboundary accords have undergone several iterations involving diplomatic note exchanges and adjustments to new climate-related challenges. The TWINS analysis and the literature review highlighted relapses in diplomatic cooperation, which demanded more frequent interaction and eventually set the foundations for cooperative engagement. In particular, we noted how the historical evolution of relationships across the border necessitated the alternation of conflict and cooperation. This observation confirmed the arguments made by Schiff [31] and Mirumachi et al. [46]. Also, with regard to knowledge sharing, our observations aligned with the concerns voiced by a cohort of climate experts mentioned earlier in the Introduction [22,25,26,57]. According to the latter, the uncertainty of climate impacts increases the complexity of diplomatic exchanges across transboundary aquifers. In this study, we advanced the knowledge on the topic as we found that the presence of a super partes, coordinating body—which, in this case, is the IJC—can facilitate the avoidance of friction over growing climate concerns and of latent conflict [37]. Establishing groundwater health thresholds in the North–North case study is a good example supporting the claim.

Especially in the context of indicators 1 and 2, the involvement of grassroots or NSA members seems to be relevant to the outcome of aquifer management. In the MRTA, the involvement of native inhabitants and First Nation representatives in the governance

space was reported to have been successfully implemented and facilitated by the use of hydro-diplomatic practices. The literature review highlighted discord between official IJC documents and what the public has stated through informal channels. Several authors [34,52] have voiced significant concern for the restriction of the agency and executive power of indigenous members of the IJC, substantiating the suspicion that their de facto marginalization is being masked by tokenism. Hydro-diplomatic practice, in theory, addresses power imbalances and the colonial legacies imprinted in rules of social interaction in political spaces [22,32–34]. In practice, it may take more than the hydro-diplomacy to break the historical marginalization of indigenous leaders in transboundary aquifers. Future research is needed to collect primary data to validate or correct the proposed speculation. We invite scholars from the field of colonial and gender studies to analyze the narrative present in the IJC reports, as opposed to the experience of First Nation representatives. We explored—informed by Woodhouse [23] and Zeitoun [22]—whether the current state of participative processes may halt the acceleration of adaptive groundwater governance.

Regarding limitations, the case study also showed diplomatic resilience to climate impacts thanks to the constant interaction between transboundary epistemic communities. Universities and private research institutes appear to be the most active drivers of cross-border exchanges across time. Still, in our study, it remains unclear whether the involvement of non-state actors has been as relevant in the implementation of hydro-diplomatic practice in the region. Our assessment did not allow for a complete analysis of the direct and indirect drivers operating in this space due to the time constraints of the exercise. It remained limited in identifying relevant stakeholders and tracing their impact on the observed system. It invites future studies to select an appropriate framework for mapping and pinning down NSAs in the North–North case study region. We suggest using a matrix able to capture the power, legitimacy and salience of stakeholders, to identify those holding de facto power in the arrangement of groundwater governance.

We also suggest that further research teams conduct literature reviews not exclusively in English. Also, as Zeitoun and Warner [27] mention, some actors' hegemonic power over others in a watershed can be exerted by creating and sharing skewed descriptions of the historical development of transboundary cooperation. Relative to the North–North case study, nearly all official sources published through official channels are written in English and match the research string we used to elicit data. We speculate that using key words in the native language of the local inhabitants may give way to alternative narratives and offer a better answer to our principal research question.

4.2. Second Transect: North-Meso Case Study

The analysis of the North-Meso case study reiterated the claim presented by Schiff et al. [31], whereby the long-term engagement in hydro-diplomatic practice between the US and Mexico has granted the SPTA a stable framework for water governance [44]. In this cross-border regional arrangement, scheduled and recurrent interactions over technical interventions in the aquifer enhanced the trust between parties, even in the absence of a central orchestrating body such as the IJC. We speculated that the successful governance of the aquifer may be due to the existence of a vertical distribution of power (NSAs, civil parties etc.), making up for the lack of a governing transboundary network. Therefore, we recommend that future research includes primary data collection through stakeholder interviews, workshops, and fieldwork. This approach will enable a more comprehensive mapping of the interactions between sub-national actors and formal institutions, providing more significant data points, particularly with indicators 2 and 4.

Regarding indicator 1, we assessed that universities and research centers had driven the knowledge-sharing practices between the US and Mexico as part of the TAAP project. Knowledge exchanges and coordinated data collection efforts on groundwater safety have, for example, led to the establishment of Active Management Areas (AMAs) and secured a 10-year funding grant from the US Congress. We claim that the decentralized nature of groundwater administration on both sides of this border has enabled a long-term

collaboration, defying disagreements on other matters of national security, immigration (e.g., politics around illegal border crossings), or finance (e.g., NAFTA). Moreover, the focus of transboundary exchanges has been set on technical matters, releasing commissioners from involvement in each other's national politics. This setup may be a helpful governance strategy for countries where foreign policy drives transboundary frictions.

The proliferation of cross-boundary disputes in the North-Meso American case study is familiar to this region. Our temporal analysis highlighted the frequent occurrence of relapses in the progress of transboundary collaboration in this region. As stated in Kuzdas et al. [37], increased civic dissent and manifest disputes may be a symptom of the presence of latent conflicts, from which we gather that local demands are not being vertically integrated in high level policy discussions. Through protest, local demands related to groundwater use are acknowledged by the governance actors, raising the level of politicization of the matter to the national political agenda [35]. Considering the region's experience with drought and surface water stress, we speculate that the recent increase in contestation of groundwater governance may be due to the severe impacts of climate change on the region. This phenomenon underlines the importance of opening cooperative hydro diplomatic channels which include non-state actor representatives, not just for water security but also for the sake of socio-political stability.

The enduring nature of diplomatic relations, mainly through non-state actors' (NSAs) pressure, has persisted for nearly a century. Wilder et al. [44] suggest that these enhanced diplomatic ties, even in areas unrelated to groundwater health, have significantly strengthened regional relationships and addressed institutional asymmetries at various levels (supranational to local). This foundation of trust and collaboration is vital for fostering lasting cooperation between nations and communities. To further this understanding, we propose conducting additional research focused on mapping actor networks and evaluating the influence of trade agreements, such as the North American Free Trade Agreement (NAFTA), on the acceleration of environmental agreements in the context of climate change. Such investigations could illuminate how economic partnerships and regulatory frameworks interact with environmental governance, potentially leading to more effective and equitable solutions for shared resources. By exploring these dynamics, we can better understand the pathways through which diplomatic relations and trade agreements can facilitate cooperative environmental action amidst the challenges of climate change and other direct and indirect factors.

4.3. Third Transect: Meso-South Case Study

The absence of robust institutions dedicated to water management in the meso-South case underscores the challenges faced in fostering collaborative efforts and knowledge sharing across borders [58]. The lack of national initiatives at the national level can explain the poor performance in collaborative knowledge production in the meso-South case. Guatemala and Belize do not have institutions for managing and protecting aquifers, or institutions focused on raising awareness concerning groundwater resources. Therefore, it is unrealistic to anticipate cross-border knowledge endeavors when these initiatives are lacking at the national level. Furthermore, the limited number of institutions dedicated to water management in each country lack a clear understanding of their roles at the basin level. The knowledge about aquifers' significance, whereabouts, and management is limited [56], and a lack of transboundary institutions to encourage knowledge production and a shortage of epistemic communities create ideas that can ultimately reach decision makers in this transitional aquifer. Knowledge production is a valuable tool for encouraging the formation of water management systems, developing a shared understanding of international rivers and establishing an independent source of science that can influence policymakers' strategies [57]. The absence of treaties or formal agreements in the meso-South case suggests that epistemic communities have not been granted space for exchange over shared water resources [59].

Moreover, the lack of engagement from local actors and the absence of discussions at the tri-national level in the meso-South case contribute to ineffective governance of groundwater resources, could affect the development of policies for this natural resource, and lead to decision making lacking scientific insights on the potential strategies for managing transboundary aquifers. Also, from legal and governance terms, there is no input to justify and support groundwater-related policymaking that applies across border regions. However, the International Groundwater Resources Assessment Centre (IGRAC) highlights the importance of raising awareness about groundwater governance beyond the executive branches of governance. The lack of scientific insights and stakeholder engagement can lead to decisions that do not adequately address the complexities of groundwater management, and power dynamics can significantly influence the outcomes of transboundary interactions. Without established data sharing and cooperation mechanisms, states may struggle to develop equitable and effective policies for managing transboundary aquifers. Without the involvement of experts and the establishment of joint monitoring programs, the management of transboundary aquifers can suffer from significant gaps in knowledge and coordination. This lack of scientific insights can hinder effective decision making and policy development, as there would be insufficient data to inform stakeholders about the significance, challenges, and potential strategies for managing these vital resources [60].

Lindemann [57] reflects on institutional frameworks and political will as vital for fostering network formation among states and non-state actors in transboundary water governance. Regarding networks and actors, the findings were limited, with no evidence of stakeholder involvement in the CILA commissions in both borders. One aspect that stands out is that groundwater discussions are absent at the tri-national level and are only poorly discussed nationally in Mexico. Therefore, local actors are not involved in addressing groundwater issues, which could lead to a lack of connections between states and non-state entities across borders [61].

Furthermore, the absence of transnational networks can also be attributed to the limited economic interdependence of the groundwater resources in these countries. The economic interdependence of regions sharing water bodies often leads to forming governance networks to ensure stable and predictable access to water [62,63] Still, in the meso-South case, there is no evidence of substantial economic activities depending on this water resource. This can result in a lack of interest in managing transboundary groundwater resources in this area. Effective management of transboundary aquifers often relies on establishing governance frameworks that are motivated by mutual economic interests. When regions share significant economic ties related to water resources, they are more likely to collaborate and form governance networks to ensure stable access. Conversely, the lack of substantial economic activities dependent on shared groundwater, as noted in the results, can lead to disinterest in cooperative management efforts [60]. Economic interdependence often drives states to form governance networks to ensure stable and predictable access to water resources [47]. Since between Mexico, Belize, and Guatemala, there are no shared economic activities depending on the transboundary water resources, there is a lack of incentive to promote governance arrangements. Without compelling economic reasons or institutional support, states may not prioritize managing shared resources, leading to fragmented governance [64].

Effective management of transboundary aquifers requires significant investment in engineering and technology to ensure the sustainable use and protection of these vital resources. However, many countries, particularly those with limited financial means, struggle to allocate sufficient funds for such initiatives. This situation can lead to inadequate infrastructure and monitoring systems, which are essential for managing shared water resources effectively [60]. Often, countries prioritize immediate national needs over long-term collaborative investments [59,65]. This seems to be the situation in the meso-South case. The lack of financial commitment in this region can be attributed to competing demands on national budgets, which is a common challenge in less developed countries. When countries face significant internal pressures, such as poverty alleviation, infrastructure

development, and social services, allocating funds for transboundary water management may not be prioritized [59]. This economic constraint often results in inadequate funding for groundwater governance [57]. Second, while international organizations and donors provide some financial support, it is usually insufficient to meet the extensive needs of transboundary groundwater projects. However, no evidence exists of international economic support for Mexico, Guatemala, and Belize aquifers.

Insufficient understanding of groundwater's significance can lead to inadequate investment in governance structures and management practices, ultimately jeopardizing the sustainability of these vital resources. Moreover, effective groundwater governance requires informed and coordinated actions by various stakeholders, including policymakers and the public [60]. Without a solid understanding of the challenges and potential strategies for managing groundwater, there is a risk of under-investment in necessary governance frameworks and technologies, as noted in our results.

4.4. Summary of Main Points and Key Observations

Our assessment suggests that the absence of a cohesive epistemic community, common concerns among stakeholders, and a shared sense of crisis may hinder collaborative efforts to address groundwater-related challenges effectively. Understanding these dynamics is essential for developing hypotheses based on the transect analysis conducted in the study. By identifying these factors, our research clarifies the lack of support for joint initiatives and proposes pathways to enhance engagement and cooperation among diverse stakeholders for boosting regional groundwater governance. This point extends to informing future research and policy development, as it underscores the importance of fostering a unified response to climate change that resonates with the experiences and concerns of affected communities in the context of surface water and groundwater. This study can serve as a foundation for exploring the integrated dimensions in 'water-focused' climate action, emphasizing the need for a collective approach to bridge understanding gaps and mobilize support across different freshwater and groundwater systems in cross-border regions. As noted in the knowledge production section, there is no clear understanding of the transnational aspect of water resources in Mexico, Belize, and Guatemala, and only Mexico and the USA have shown some effort to address groundwater resource issues. This factor has been observed to underwhelm policymakers and affect the allocation of financial resources for hydro-diplomacy to the small aquifers affected by climate change impacts.

Regarding the transboundary joint bodies in the meso-South case, the results can indicate how economic constraints limit their ability to invest in joint governance bodies. Establishing and maintaining these transnational institutions requires significant financial resources for research, monitoring, capacity building, and infrastructure development [38,66]. It is relevant to note that according to the World Bank, Guatemala and Belize have quite low GDP per capita and weak economies compared to the USA and Mexico. These economic constraints can often lead to competing national priorities, with countries focusing their limited resources on pressing domestic issues rather than collaborative transboundary governance.

States tend to cooperate when the net economic and political benefits outweigh the benefits of unilateral action [62,67]; likely, groundwater resources do not represent a significant or essential source of income for Guatemala, Mexico, and Belize, hindering progress in the advancement toward adaptive groundwater policies. This issue contributes to a lack of focus on aquifers in the transnational agenda, highlighting the need for increased attention to hydro-diplomatic practices that could facilitate better management of shared water resources and strengthen cooperation among neighboring countries.

Limitations in collaboration practices and knowledge production endeavors across the bordering countries were also detrimental to the volumes and consistency of data which we could consult. For instance, while we found rich and detailed information on transboundary cooperation in the northern case study, data were sparse and limited for the southern case. This discrepancy impacted our ability to assess hydro-diplomacy's role

across all regions fully. Despite this, we qualitatively evaluated its impact on transboundary groundwater governance using the TWINS matrix, board trends, and patterns derived from the literature review and compared regions with positive outcomes on SDG 6 indicators to those with less successful results, thereby assessing which components of hydro-diplomacy facilitate better transboundary water governance outcomes.

5. Conclusions

Transboundary groundwater governance is a complex challenge for modern societies in efficiently managing cross-border water systems (socioeconomic, hydrological factors). This challenge underscores the need for a comprehensive understanding of governance mechanisms and highlights specific policy gaps that hinder the effective management of transboundary aquifers. Addressing the intricacies of transboundary groundwater governance requires focusing on policies that enhance context-specific regional and global cooperation. As selected case studies explain, identifying priorities and gaps in water governance is pertinent. Also, implementing frameworks like the joint monitoring committees, as noted for the US–Mexico, is crucial for developing effective strategies. In this assessment, we also examine patterns in various settings of transboundary aquifers that reveal contextual variables' influence on institutional design, highlighting a critical need to bridge knowledge gaps in regional groundwater governance. Furthermore, managing transboundary groundwaters necessitates supporting intersectoral dialogues and assessments and applying integrated approaches such as the water–food–energy nexus. We reiterate that addressing policy gaps is vital to fostering sustainable and equitable shared water resource management.

Overall, our findings underscore the complexity of transboundary groundwater governance, highlighting the importance of understanding specific policy gaps and the influence of socio-cultural contexts on institutional design. The limitations of our study—such as the variability in data availability and regional differences—suggest the need for further research involving direct stakeholder engagement, to better understand hydro-diplomacy's role in diverse socio-hydrological contexts. Future studies should consider incorporating new indicators and interdisciplinary perspectives, including group psychology and digital anthropology, to improve the explanation of the nexus between diplomatic practices and trust-building dynamics under climate change pressure along the transect. Particular attention should be given to how digital development may be an enhancing factor for the creation of transboundary epistemic communities, on the one hand, and the encouragement of cross-border financial investments due to higher transparency on the other. With this paper we decided to only tap into the spheres of hydrology and diplomacy alone, contributing to advancements in climate studies, public policy, geopolitics operating at the regional level, and water diplomacy.

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Appendix A

Table A1. Hydro-geological and demographic data describing the Milk River Aquifer, San Pedro Transboundary Aquifer, and Yucatán Peninsula Aquifer.

Milk River Transboundary Aquifer (MRTA)		**San Pedro Transboundary Aquifer (SPTA)**		**Yucatán Peninsula Aquifer (YPA)**	
Transboundary border	CA-USA	Transboundary border	US-MX	Transboundary border	MX-GT-BZ
Total Surface Area (km^2)	25,000	Total Surface Area (km^2)	5000	Total Surface Area (km^2)	165,000
Alberta (Can)	11%	Arizona (USA)	2460	Mexico	5.41%
Saskatchewan (Can)	24%	Sonora (Mex)	2892	Guatemala	70%
Montana (U.S.A)	65%			Belize	21.44%
Mean Annual Precipitation (mm/y)	250 to 450	Mean Annual Precipitation (mm/y)	330 to 960	Mean Annual Precipitation (mm/y)	1200
Mean Evapotranspiration (mm/y)	550 to 578	Mean Evapotranspiration (mm/y)	~200		
Total groundwater withdrawals (m^3/y)	1.2×10^6	Total Dissolved Solids (mg/L) Potassium (ppm)	0 to 5	Mean Evapotranspiration (% of total precip.)	40–85
Alberta	<2	Total wells	5000+	Total Dissolved Solids (mg/L)	1.001–2.000
Total Dissolved Solids (mg/L)—Eastern MRTA	270 to 3400	Total Population	97,235	Total Population	3,800,000
				Maya	67%
Pollution source	Industry, agriculture	Pollution source	Industry, agriculture, livestock	Pollution source	Tourism, agriculture, urban wastewater
Total Wells	1000+	Climate	Arid to semi-arid	Climate	Sub-humid
Climate	Semi-arid	Groundwater recharge mechanism	Percolation and exchanges with perennial water courses	Topography	Calcareous soil and downward slope profile
Topography	Corrugated, sandy, permeable soils, outcrop areas				
Total Population	10,706				
Blackfeet Reservation	3827				
Rocky Boy's Indian Reservation	3627				
Fort Belknap Indian Reservation					

Table A2. Research strings describing the approach to Phase 1.

Strings	Scoping Review	Literature Review
Hydro-diplomacy	Hydro-diplomacy * AND Americas Hydro-diplomacy * AND Canada* OR United States * OR Latin America * OR South America Hydro-diplomacy * AND Diplomacy * OR History * OR Development Hydro-diplomacy * AND groundwater; water quality; water stress; water pollution	Hydro-diplomacy * AND Milk River Aquifer * OR Milk River * OR MRTA * AND transboundary Water diplomacy * AND Milk River Aquifer * OR Milk River * OR MRTA; USA; Canada Hydro-diplomacy * AND San Pedro Aquifer; Mexico; USA*; AND transboundary Hydro-diplomacy * AND Yucatan Peninsula Aquifer; YPA; Mexico; Belize; Guatemala *; AND transboundary Hydro-diplomacy * AND Varady; Rivera
Hydro-hegemony	Water * AND Power Hydro-hegemony * AND America * OR Latin America; Mexico * AND South America; Mexico; Belize; Guatemala	Hydro-hegemony * AND upstream; downstream; dynamics; control
Indigenous studies	Indigenous * OR First Nations * AND Water; Diplomacy; hydro-diplomacy	Indigenous * OR First Nations * AND hydro-diplomacy; participation; policy; policy processes; law *; AND groundwater
Hydrology and climate	-	Hydrology * AND Milk River Aquifer * OR Milk River * OR MRTA Hydrological cycles * AND Milk River Aquifer * OR Milk River * OR MRTA Milk River Aquifer * OR Milk River * OR MRTA * AND Climate region; precipitation; temperature; soil composition; topography Hydrology * AND Milk River Aquifer * OR Milk River * OR MRTA * AND groundwater; wells; unmanaged withdrawals; private wells
Diplomatic history	-	Hydro-diplomacy * AND Milk River Aquifer * OR Milk River * OR MRTA * AND transboundary diplomacy; diplomatic exchanges; water diplomacy; water treaty; water quality treaty; agreement San Pedro Aquifer; Mexico; USA * AND transboundary diplomacy; diplomatic exchanges; water diplomacy; water treaty; water quality treaty; agreement Yucatan Peninsula Aquifer; YPA; Mexico; Belize; Guatemala * AND transboundary diplomacy; diplomatic exchanges; water diplomacy; water treaty; water quality treaty; agreement
Institutional set up	IJC * OR International Joint Commission * AND Canda; USA; United States	IJC* OR International Joint Commission * AND Canda; USA; United States * AND Boards; mandate; members; power; jurisdiction * AND indigenous; participation; deliberative processes

Table A3. Stakeholder overview of three case studies across the American transect. Stakeholder mention under a specific column signifies their contribution to the sub-dimension of transboundary cooperation indicated with Ix.

	Transboundary Social Learning and Knowledge Production (I1)		**Transboundary State and Non-State Actor Networks (I2)**		**Transboundary Financial Commitment to Engineering and Technology (I3)**		**Transboundary Joint Bodies (I4)**	
	Institution or Projects	**Stakeholders or Groups**	**Institution or Projects**	**Stakeholders or Groups**	**Institution or Projects**	**Stakeholders or Groups**	**Institution or Projects**	**Stakeholders or Groups**
North–North (MRTA)	International Joint Committee	Water Survey Division of Environment Canada and the U.S. Geological Survey, water managers, Accredited Officers (i.e., governmental representatives), Indigenous representatives	City of Havre Public Works Department, Milk River Watershed Alliance, Milk River Board of Control, Blaine County Conservation	Indigenous representatives, Public, governmental representatives, independent reviewers, technical advisors (engineers, hydrologists, infrastructure experts etc.)	International Joint Commission: $5 million from US-CAN for the period 2015–2020 for implementation of IWI approach	Supra national institution	International Joint Committee	Water Survey Division of Environment Canada and the U.S. Geological Survey, water managers, Accredited Officers (i.e., governmental representatives), Indigenous representatives
	International St. Mary and Milk Rivers Study Board	Indigenous representatives, Public, governmental representatives, independent reviewers, technical advisors (engineers, hydrologists, infrastructure experts etc.)	District Montana State University-Extension, Milk River Water Users Association, Rural Municipalities of Alberta, Milk River Watershed, Council of Canada Alberta Irrigation Districts Association, Oldman Watershed Council, Saskatchewan Irrigation Projects Association		Alberta Environment: $293,463 for closing free-flowing wells	Governmental agency	Miritap Project	Municipal and provincial representatives, academia, technical advisors, indigenous representatives
	Milk River Watershed Council Canada	NGO, public, Provincial Government, Academia, Recreation experts, Federal government, private sector, health representative, farmers, municipal district, first nations representative, rural/urban municipality representative.			Town of Forty Mile: $100,000 for closing free-flowing wells	Local government		
	Miritap Project	Municipal and provincial representatives, academia, technical advisors, indigenous representatives			Agriculture and Agri-Food Canada: $293,463 to the strengthening of transboundary groundwater infrastructure	Governmental agency		

Table A3. *Cont.*

	Transboundary Social Learning and Knowledge Production (I1)		**Transboundary State and Non-State Actor Networks (I2)**		**Transboundary Financial Commitment to Engineering and Technology (I3)**		**Transboundary Joint Bodies (I4)**	
	Institution or Projects	**Stakeholders or Groups**	**Institution or Projects**	**Stakeholders or Groups**	**Institution or Projects**	**Stakeholders or Groups**	**Institution or Projects**	**Stakeholders or Groups**
North-Meso (SPTA)	International Boundary and Water Commission (IBWC)	State Government (MX and US)	Transboundary Aquifer Assessment Program (TAAP).	US and MX federal government, state agencies, US state government representatives, university researchers, technical advisors	50 million USD approved by the US congress for TAAP (for 10 years over 3 different aquifers)	US states and MX national government	International Boundary and Water Commission (IBWC)	State Government (MX and US)
	CONAGUA	National regulatory body (MX)	WHYMAP program	Supranational actors, federal government, states, international research centers, freelance contributors	$160,000 from CONAGUA for TAAP (over 3 different aquifers)			
	Transboundary Aquifer Assessment Program (TAAP)	University alliance						
	International Boundary and Water Commission (CILA)	National Governments	UNESCO/OAS ISARM Americas program transboundary aquifers of the Americas	National coordinators of the 20 countries participating in the project, technical experts	Mexico 1.5 billion dollars (budget manage at the national level)	National governments	International Boundary and Water Commission (CILA)	National governments (MX-BZ-GUAT)
Meso-South (YPA)	UNESCO/OAS ISARM Americas program transboundary aquifers of the Americas	UNESCO/OAS Academia Public sector	CONAGUA programs for GW management (MX-GUAT)		GUAT+BZ: 30 million dollars (budget managed at the national level)			
					World financial agencies (Global Environment Facility, or GEF, World Bank) supported ISARM activities			

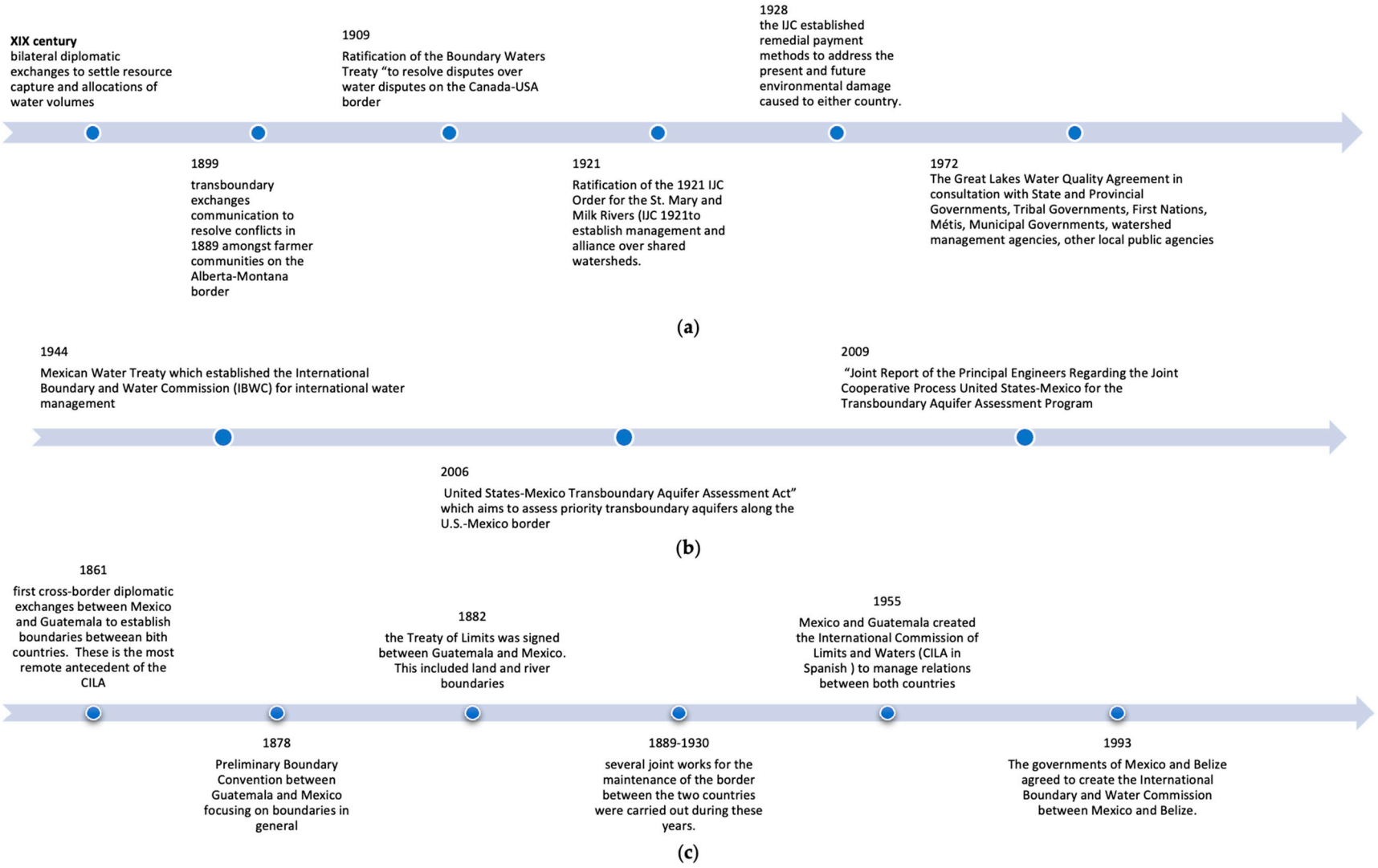

Figure A1. Progression of complexity of hydro-diplomatic exchanges—(**a**) Milk River Aquifer, (**b**) San Pedro Aquifer, (**c**) Yucatan Peninsula Aquifer.

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