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The U.S.-Mexico Transboundary Aquifer Assessment Program as a Model for Transborder Groundwater Collaboration

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Abstract: The assessment of transboundary aquifers is essential for the development of groundwater management strategies and the sustainable use of groundwater resources. The Transboundary Aquifer Assessment Program (TAAP) is a joint effort by the United States and Mexico to evaluate shared aquifers. This study examines the TAAP Cooperative Framework as a guide for further transboundary groundwater collaboration. We compared lessons learned from six transboundary aquifers that currently have mechanisms for groundwater collaboration to identify common elements of collaboration. Though the TAAP Cooperative Framework governs an assessment-only program, the elements of collaboration included are consistent with the principles of other institutional agreements around the world. Importantly, all the analyzed agreements included a knowledge-improvement phase, which is the main objective of the TAAP Cooperative Framework. The present study finds evidence of successful outcomes within the TAAP Cooperative Framework consistent with available transboundary groundwater management agreements, demonstrating that this approach is suited to serve as a model for those wishing to engage in transborder aquifer assessments. Furthermore, the TAAP elements of collaboration can help to establish the meaningful and robust binational cooperation necessary for the development of U.S.-Mexico groundwater management agreements at the aquifer level.

Keywords: transboundary aquifers; United States; Mexico; assessment; agreements; groundwater management

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1. Introduction

Groundwater is an important source of fresh water for populations and the environment. Fresh water represents only 2.8% of the total water resources in the world, with 70% of fresh water composed of polar ice layers and continental ice, 1% from surface water-courses, and 29% from groundwater [1]. Transboundary rivers, lakes, and aquifers are home to over 70% of the world's population and supply water for around 60% of global food production [2]. Approximately 600 transboundary aquifers have been identified around the world [3]. However, only six of them have formal binational or multinational mechanisms of cooperation: (1) the Guarani Aquifer System in Brazil, Argentina, Paraguay, and Uruguay; (2) the Franco-Swiss Genevese Aquifer System in France and Switzerland; (3) the Northwestern Sahara Aquifer System in Algeria, Libya, and Tunisia; (4) the Iullemeden Aquifer System in Mali, Niger, and Nigeria; (5) the Nubian Sandstone Aquifer System shared by East Libya, Egypt, Northeast Chad, and North Sudan, and; (6) the Al-Saq/Al-Disi Aquifer System in Jordan and Saudi Arabia (Figure 1).

Although geographically widespread, these aquifers represent only 1% of identified transboundary aquifers, a proportion that is quite different from the proportion of transboundary river basins with international basin agreements. While there are 310 transboundary river basins around the world, a total of 688 transboundary basin agreements

have been signed between 1820 and 2007 [4–6]. These agreements apply to 133 river basins, representing 36% of the identified transboundary basins [4]. The reasons for such a disparity between the number of basin agreements and the number of groundwater agreements include the “invisible” nature of groundwater [7,8], limited and dissimilar groundwater data [9], and the lack of institutional capacity for groundwater governance [10].

Groundwater collaboration between the United States and Mexico is similar to other transboundary settings around the world. Efforts by the two countries to understand and manage groundwater resources have been scarce and sporadic [11]. The two countries have a surface water agreement, the 1944 Water Treaty Regarding the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (1944 Treaty); however, groundwater was left unmentioned. Only Minute 242 was approved in 1973 by the International Boundary and Water Commission (IBWC), one of many interpretations of the 1944 Treaty includes a provision that is relevant to groundwater. The IBWC is the international body that oversees the application of U.S.-Mexico treaties related to boundary demarcation, national ownership of waters, sanitation, water quality, and flood control in the border region [12]. Challenges in the management of groundwater resources in the U.S.-Mexico border region include rapid urbanization and industrialization, agricultural intensification, contamination of surface and groundwater resources, increase in surface and groundwater demands, and climate uncertainties [13–15]. These challenges indicate the need for binational transboundary collaboration to secure water for populations and the environment. Such a collaboration could take the form of a binational agreement for the management of groundwater resources. However, scholars have recognized that the assessment of shared aquifer systems is a necessary antecedent to the development of any groundwater management agreement [8,16–19]. For example, Kirstin I. Conti [18] indicated that scientific research is an enabling factor for groundwater cooperation, along with existing legal mechanisms, regional institutions, high institutional capacity, funding mechanisms, strong political will, previous water cooperation, and third-party involvement.

The Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program (TAAP Cooperative Framework) [20], guides the joint effort between the United States and Mexico to improve the knowledge base of transboundary aquifers. The program began in 2006 with the Transboundary Aquifer Assessment Act (U.S. Public Law 109–448, TAA-Act). The TAA-Act authorized the United States Geological Survey (USGS) and the Water Resources Research Institutes (WRRIs) of Arizona, New Mexico, and Texas to work with Mexican counterparts on the development of transboundary aquifer assessments. The TAA-Act authorized U.S. involvement in binational studies of the Santa Cruz and San Pedro Aquifers, shared by the state of Arizona in the United States and the state of Sonora in Mexico, and the Mesilla and Hueco Bolson aquifers, shared by the states of Texas and New Mexico in the United States and the state of Chihuahua in Mexico (Figure 1). These priority aquifers were selected based on their proximity to highly populated areas, increasing groundwater demands, and water quality issues [21]. The binational TAAP was formally initiated in 2009 upon the signing of the TAAP Cooperative Framework by the principal engineers of the U.S. and Mexican sections of the IBWC. The two countries agreed upon the TAAP aquifers of focus consistent with the TAA-Act priority aquifers (Figure 1). According to the TAAP Cooperative Framework, either of the two countries can propose an aquifer of focus, but both countries must agree to develop a joint assessment.

The TAA-Act and the TAAP Cooperative Framework offer a foundation for collaboration to study shared groundwater resources through an effective partnership among federal agencies, academic institutions, and federally established water resources research institutes [21,22]. The TAAP can also be considered a climate and water adaptation initiative for the western U.S.-Mexico border [13], a transboundary regional initiative that has the potential to build adaptive capacity [15], an activity that can support decision-making

processes related to groundwater management in each country [23], and a precedent for a binational partnership that can promote and implement a new binational aquifer assessment [9]. However, the relevance of the TAAP Cooperative Framework as a model mechanism for groundwater collaboration has not been fully addressed in the literature.

The TAAP Cooperative Framework is limited to assessment only, with four transboundary aquifers studied to date. The Map of Transboundary Aquifers of the World [3] includes 11 shared transboundary aquifers along the border between the United States and Mexico. Yet, a review of technical studies, reports, and publications on U.S.-Mexico transboundary aquifers suggest that at least 36 transboundary aquifers are shared by the two countries [24]. Clearly, additional study opportunities exist, and the activities undertaken by the TAAP can serve as the basis for assessment that goes beyond the current TAAP aquifers of focus and that can even guide future dialogue regarding groundwater governance and management [8]. The primary objective of the study is to determine whether the elements of the TAAP Cooperative Framework can serve as a model for others wishing to engage in transboundary aquifer assessment. Expert interviews and lessons learned from evaluating six existing international groundwater agreements helped to determine whether the objectives, framework/process, funding, principles, and communication arrangements of the TAAP Cooperative Framework can guide further groundwater cooperation.

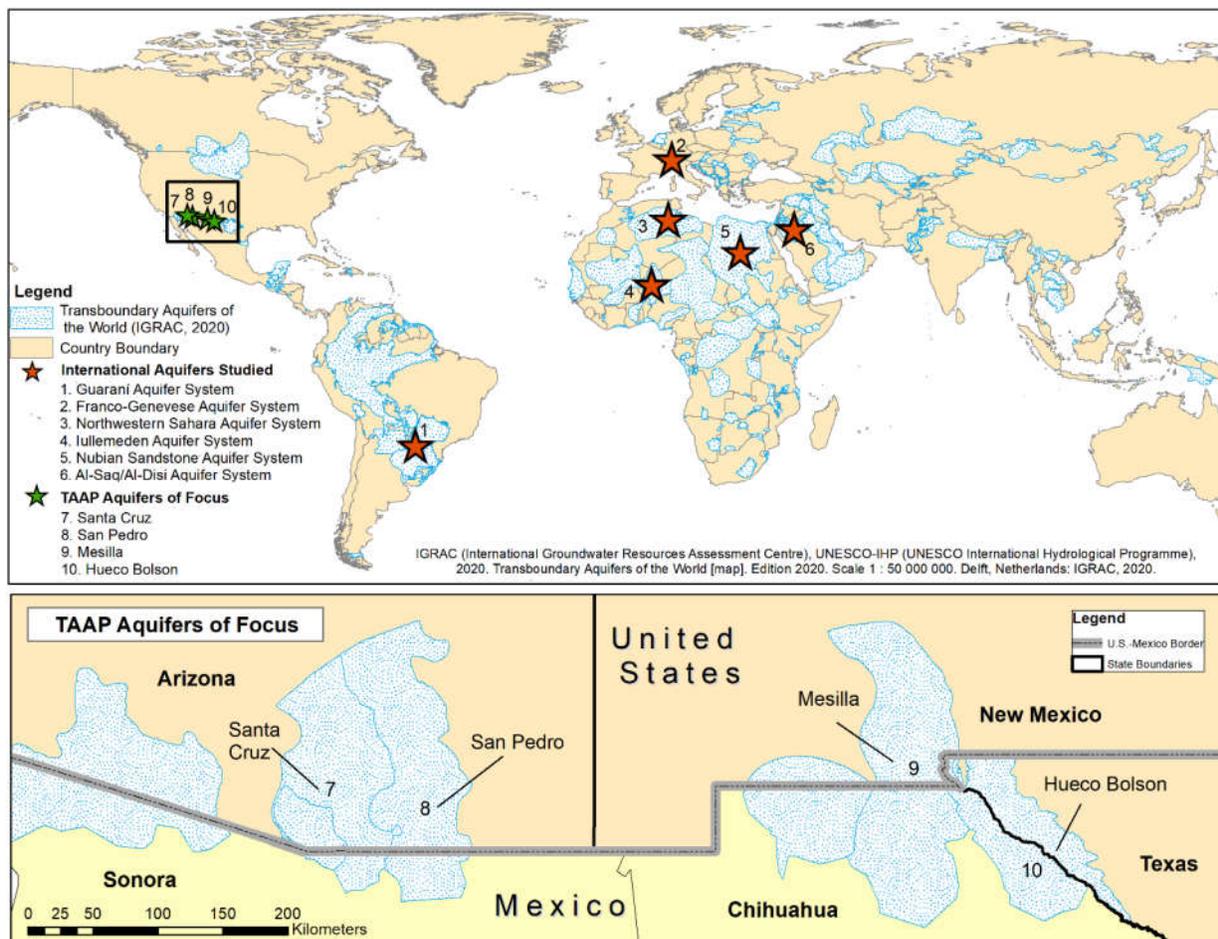


Figure 1. International Aquifers Studied and Transboundary Aquifer Assessment Program (TAAP) Aquifers of Focus, based on Transboundary Aquifers of the World [3].

2. Materials and Methods

The present work provides an assessment of the TAAP Cooperative Framework as a model for transboundary groundwater collaboration. To achieve this, we compared the elements of collaboration in the TAAP Cooperative Framework with the components of six transboundary groundwater collaboration agreements. The TAAP Cooperative Framework elements of collaboration were taken from the Joint Report of the Principal Engineers Regarding Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program (Cooperative Framework) [20]. These elements are presented in Table 1 and were used as a basis for comparison. Selected institutional governance agreements include the existing collaboration mechanisms for the following: (1) the Guaraní Aquifer System (GAS), (2) the Franco-Swiss Genevese Aquifer System, (3) the Northwestern Sahara Aquifer System, (4) the Iullemeden Aquifer System, (5) the Nubian Sandstone Aquifer System (NSAS), and (6) the Al-Saq/Al-Disi Aquifer System. These transboundary aquifers were selected because of their formal mechanisms of groundwater cooperation [17,18,25–27].

Table 1. TAAP Cooperative Framework elements of collaboration [20].

Objectives	<p>Facilitate data exchange</p> <p>Ensure the concurrence for binational aquifer assessment activities</p> <p>Facilitate agreement on the aquifers, which will be evaluated jointly</p> <p>Establish and coordinate binational technical advisory committees</p> <p>Establish an official repository for binational project reports</p>
Framework (Process)	<p>Either of the two countries can propose an aquifer to study</p> <p>The International Boundary and Water Commission (IBWC) will coordinate with agencies from both countries to jointly define the scope of the assessment</p> <p>Binational technical groups will be established and coordinated by the IBWC</p> <p>The IBWC will facilitate concurrence of joint work plans</p> <p>Whoever carries out the joint studies will update the binational technical groups with the project progress</p> <p>The final reports that proceed from the joint studies will be published in English and Spanish and will be made available for publication once they have been approved within the IBWC framework</p>
Funding	<p>Each country will be responsible for any costs on projects conducted in its territory</p> <p>Either country may contribute to the costs of work done in the other country</p> <p>Contributions will be distributed according to the process agreed on through the IBWC</p> <p>All projects and measures considered are subject to the availability of funds</p>
Principles	<p>Activities should be beneficial to both countries</p> <p>Activities should be agreed on within the framework of the IBWC</p> <p>Activities should respect the legal framework and jurisdictional requirements of each country</p> <p>No provision set forth in this agreement will limit what either country can do independently in its own territory</p> <p>No part of this agreement may contravene what has been stipulated in the boundary and water treaties</p> <p>The information generated from these projects is solely for the purpose of expanding knowledge</p>
Communication	<p>The IBWC will be an official repository of records</p> <p>The final joint binational reports will be available to the public in each country and will be posted on the website of each section of the IBWC</p> <p>Information obtained should be considered as official data and should be shared without any restrictions</p> <p>Credit will be given to those who provide information</p>

Stakeholder interviews implemented during 2019 and 2020 served to identify whether TAAP lessons can be generalized to other aquifers along the U.S.-Mexico border and elsewhere. The selection of participants was based on purposive sampling. This non-random technique does not need a set number of participants and interviewees are selected according to the qualities or knowledge they possess [28]. Interviewees consist of two IBWC experts (interview 1 and 2), two experts in political sciences (interview 3 and 4), and two researchers/scientists (interview 5 and 6). Selected interviewees were familiar with transboundary aquifer assessment and management and with the principles of the TAAP Cooperative Framework. Interview questions included:

- According to your experience, what factors promote the successful groundwater collaboration between nations that share one or various aquifers?
- Do you think we can generalize the TAAP principles of collaboration to other aquifers within the U.S.-Mexico border?
- Do you think the TAAP Cooperative Framework can serve as a model for the assessment of other transboundary aquifers?
- Do you think the TAAP Cooperative Framework can serve as a basis for the development of future groundwater management agreements in the borderlands of the United States and Mexico?

3. Results

This section describes the history of transboundary groundwater collaboration around the world and the mechanisms of collaboration included in the analyzed groundwater agreements. We also present a comparison of the elements of the TAAP Cooperative Framework and the components of the six analyzed aquifer agreements. Expert interviews regarding the applicability of the TAAP Cooperative Framework to others contemplating transborder collaboration are also reported in this section.

3.1. Transboundary Groundwater Resources and International Law

Some of the international guidelines related to transboundary groundwater resources include the 1966 Helsinki Rules, the 1986 Seoul Rules, the 1997 UN Convention on the Law of the Non-Navigational Uses of Transboundary Watercourses (UN Watercourses Convention), the 1999 Convention on the Protection and Use of Transboundary Watercourses and International Lakes, the 2004 Berlin Rules, and the 2008 Draft Articles on the Law of Transboundary Aquifers [29–31]. These guidelines serve as a reference for groundwater management. However, only some of them recognize the connection between surface water and groundwater. For example, the UN Watercourses Convention addresses surface water and groundwater but fails to recognize confined aquifers [30]. The Convention on the Protection and Use of Transboundary Watercourses and International Lakes also fails to recognize confined transboundary aquifers even though it documents the importance of groundwater in the management of drainage basins [29].

The 2008 Draft Articles on the Law of Transboundary Aquifers (UN Draft Articles) do recognize confined aquifers [1,32,33]. Among many provisions, the UN Draft Articles include principles related to the sovereignty of the countries sharing an aquifer (Article 3), provisions for equitable and reasonable utilization of groundwater resources (Article 4), the obligation not to cause significant harm (Article 6), a general obligation to cooperate (Article 7), requirements for the regular exchange of data and information (Article 8), stipulations for the protection and preservation of ecosystems (Article 10), and guidelines for monitoring (Article 13). The United Nations General Assembly (UNGA), however, has not ratified the UN Draft Articles, though the item has been on its agenda several times in it will be again in 2022 [8]. Partly in response to this development in international law, other cases of groundwater collaboration mechanisms have been signed between coun-

tries [8]. For example, the Guaraní Aquifer System Agreement and the Bamako Declaration for the Iullemeden Aquifer System both refer to the UN Draft Articles [8,32]. Below, we present a summary of the mechanisms analyzed in this study.

3.2. Transboundary Groundwater Collaboration around the World

Diverse cultures, countries, and states connect to groundwater in a hydropolitical matrix that comprises the policies, social exchanges, discussions, and agreements between different nations [34]. Water allocation is a key component of water governance, and in transboundary settings, this process involves a variety of users competing in an unavoidable conflictual process [35]. The principle of equitable and reasonable utilization of water resources should guide groundwater allocation between different countries, yet there is no universal theory of justice to satisfy every water user [36].

According to the United Nations Sustainable Development Goals (SDG 6.5.2), “specific arrangements or agreements between co-riparian countries are a precondition to ensure long-term sustainable cooperation” [37,38]. In this section, we detail the six transboundary aquifers that have agreements or other arrangements established for groundwater collaboration. Table 2 presents a summary of the analyzed transboundary groundwater agreements, the countries involved, dates, and the purpose of each agreement, followed by an explanation of the main characteristics of each aquifer agreement. Focusing on the elements and history of each collaboration, we subsequently compare the agreements with the U.S.-Mexico TAAP Cooperative Framework.

Table 2. Transboundary Groundwater Agreements around the World.

Aquifer System	Agreement	Countries Involved	Date(s)	Agreement Characteristics
Guaraní Aquifer System (GAS)	Guaraní Aquifer Agreement	Argentina Brazil Paraguay Uruguay	Signed in 2010 Ratified in 2018	Promotes the sustainable development of the aquifer system Solves issues arising between countries Aligned to the UN Draft Articles
Franco-Swiss Genevese Aquifer System	Convention on the Protection, Utilization, Recharge, and Monitoring of the Franco-Swiss Genevese Aquifer	France Switzerland	1978–2008 (New convention established in 2008)	Focused on groundwater quality, quantity, and artificial recharge The only treaty to date that allocated volumes of water Developed a hydrogeologic database and model Maintains an observation network
Northwestern Sahara Aquifer System	The Permanent Consultation Mechanism for the Northwestern Sahara Aquifer System	Algeria Libya Tunisia	2008	Analyzes socioeconomic activities Develops joint studies Formulates proposals for optimization and consultation mechanisms Serves as a consultative mechanism
Iullemeden Aquifer System	Bamako Declaration	Mali Niger Nigeria	2009	Improves knowledge and strengthens regional cooperation

Al-Saq/Al-Disi Aquifer System	Agreement between the Government of the Hashemite Kingdom of Jordan and the Government of the Kingdom of Saudi Arabia for the Management and Utilization of the Ground Waters in the Al-Saq/Al-Disi Layer	Jordan Saudi Arabia	2015	Restricts groundwater extractions in protected areas Governs the digging of observational wells Controls pollution
Nubian Sandstone Aquifer System	Programme for the Development of a Regional Strategy for the Utilization of the Nubian Sandstone Aquifer System and the Terms of Reference for the Monitoring and Exchange of Groundwater Information of the Nubian Sandstone Aquifer System	East Libya Egypt Northeast Chad North Sudan	2000	Focuses on data exchange and monitoring efforts

3.2.1. Guaraní Aquifer System (GAS)

Located across four South American countries, the GAS is one of the largest freshwater reservoirs in the world [26,39]. The GAS covers an area of 1,087,879 square kilometers (km²), with the largest portion situated in Brazil, followed by Argentina, Paraguay, and Uruguay [26,40]. The breakdown of the reservoir's water resources usage is as follows: municipal water supply (66%), industries (16%), thermal tourism (13%), and irrigation (5%) [40]. The four countries sharing the aquifer are known for their collaboration regarding the La Plata River Basin [8] and have benefited from continuous research and development projects, such as the Environmental Protection and Sustainable Development of the Guaraní Aquifer System Project supported by the Organization of American States and the Common Market of the South [39,41].

The Guaraní Aquifer Agreement was signed in August 2010, but it was not ratified by all four countries until 2018. This document points to the principles described by the UN Draft Articles to promote the sustainable development of the aquifer system and to solve some of the issues that might arise in the aquifer countries. For instance, Articles 2 and 3 of the Guaraní Aquifer Agreement state that each of the parties has the sovereign right to promote the management, utilization, and monitoring of their portion of the aquifer system as long as they follow the principle of reasonable use. Data exchange and knowledge improvement are essential, as expressed in Articles 8 and 12. Finally, a commission oversees compliance by all parties with the principles of agreement [42]. Factors enabling transboundary collaboration among the countries that share the GAS include the existing regional institutions, funding mechanisms, high institutional capacity, previous water cooperation, scientific research, strong political will, and third-party involvement [18].

3.2.2. Franco-Swiss Genevese Aquifer System

The Franco-Swiss Genevese Aquifer System is shared by France and Switzerland and has an approximate areal extent of 19 km² [27]. Ten wells on the Swiss side of the aquifer and four wells on the French side supply water to the Swiss Canton of Geneva and the neighboring French Territory (Haute-Savoie). The Convention on the Protection, Utilization, Recharge, and Monitoring of the Franco-Swiss Genevese Aquifer was established in 1978 after a dramatic decrease in groundwater levels associated with groundwater pumping [18,43].

The 1978 convention focused on groundwater quality, quantity, and artificial recharge, and it is the only treaty for transboundary aquifers that allocates specific volumes of water to the involved parties [17,18,44]. Despite the lack of provisions related to sovereignty rights, each of the parties has the right to make decisions around groundwater pumping, equipment, and abstraction margins [8,38]. Recharge from the Arve River is treated and channeled into the aquifer, helping to balance a seven million cubic meters (Mm³) per year overdraft [43,45]. A joint commission oversees the preparation of groundwater management plans, the monitoring of groundwater, the efforts to gain approval for

new infrastructures, and the verification of construction and operation costs of artificial recharge facilities [17]. The commission consists of six members, at least four of whom are experts in water-related issues [17].

When the 1978 convention expired, a new convention came into effect on 1 January, 2008 [46]. This new agreement includes the French communities of Annemasse, the rural districts of Genevois, and the municipality of Viry. The fact that the 1978 convention did not include participation from the federal government of either country adds a local dimension to the arrangement that was essential for the success of the agreement [25]. Technical and scientific studies were also crucial for resolving the overexploitation problems, and they served as the basis for collaboration efforts [43].

3.2.3. Northwestern Sahara Aquifer System

Shared by Algeria, Libya, and Tunisia, the Northwestern Sahara Aquifer System has an areal extent of 1,019,000 km². The Permanent Consultation Mechanism for the Northwestern Sahara Aquifer System was signed in July 2008 by the three countries' representatives [26]. The consultation mechanism is composed of a steering committee and a scientific committee [47]. The many goals of the agreement include (1) the development of a hydrogeologic database and groundwater flow model; (2) the setup of an observation network to process, analyze, and validate data; (3) the analysis of the socioeconomic activities of the region; (4) the coordination for the development of joint studies, and (5) the formulation of proposals for optimization and consultation mechanisms [48].

Collaboration among the countries sharing the aquifer has lasted at least 45 years, with activities designed to improve scientific knowledge about the aquifer. Features of collaboration for the Northwestern Sahara Aquifer System include political will, funding, and available institutions, such as the Observatoire du Sahara et du Sahel (Sahara and Sahel Observatory—OSS) [18]. Thus far, collaborative efforts have focused on scientific studies of the aquifer, and transboundary groundwater management has not yet occurred.

3.2.4. Iullemeden Aquifer System

The Sahel region aquifers in West Africa include the Iullemeden-Taoudeni/Tanezrouft Aquifer System. Shared by Mali, Niger, and Nigeria, the Iullemeden Aquifer System has an areal extent of 525,000 km². The cooperative and financing mechanisms of the region, along with their regional institutions, have been shaped by 20 years of collaboration that has led to the development of two agreements: (1) the Protocol on Cooperation of the Utilization of the Niger River, signed by Mali and Niger in 1988, and (2) the Joint Commission for Cooperation on Equitable Sharing for Development, Conservation, and Utilization of the Common Water Resources, signed by Niger and Nigeria in 1990 [18]. Later, the Bamako Declaration for the Iullemeden Aquifer, which is a Memorandum of Understanding (MOU) that encourages collaboration between the three countries, was signed by Mali, Niger, and Nigeria in 2009. The MOU recognizes the importance of water resources for alleviating poverty, acknowledges the rights and duties of the countries sharing the aquifer, appreciates the achievements of the improvement of the scientific knowledge associated with the aquifer, and highlights the importance of cooperative management of the Iullemeden Aquifer System in improving the management of shared groundwater resources [49].

Additionally, the countries commit to adopting the principles of the equitable and reasonable use of shared groundwater resources, exchanging information, giving prior notification of planned work, and adopting environmental protection regulations [32]. This collaborative effort evolved into the development of another MOU in 2014, this time, among the countries of Algeria, Benin, Burkina Faso, Mali, Mauritania, Niger, and Nigeria, for the establishment of a Consultative Mechanism for the Iullemeden and Taoudeni/Tanezrouft Aquifer Systems (ITAS). This MOU, however, is not yet in effect, pending the signatures of three of the parties [50]. The consultative mechanisms of the

ITAS demonstrate the readiness to develop management strategies, though the agreement has not evolved into additional management actions [1,26].

3.2.5. Nubian Sandstone Aquifer System (NSAS)

The Nubian Sandstone Aquifer System consists of a series of laterally and/or vertically interconnected aquifers that extend across more than 2,000,000 km² in East Libya, Egypt, Northeast Chad, and North Sudan [17]. The formal agreements ratified by the countries sharing the aquifer include (1) the Programme for the Development of a Regional Strategy for the Utilization of the Nubian Sandstone Aquifer System and (2) the Terms of Reference for the Monitoring and Exchange of Groundwater Information of the Nubian Sandstone Aquifer System, both signed in October 2000 [47]. The NSAS projects, which are considered initial stages of groundwater collaboration, are widely supported by donors and the scientific community [51].

Though these agreements are relatively recent, the collaboration between Libya and Egypt dates back to 1991, when the Joint Authority of the Nubian Sandstone Aquifer System (JASD-NSAS) was established [47]. The first countries to join were Libya and Egypt, with Sudan and Chad following in 1996 and 1999, respectively [52]. The information shared under the NSAS agreement includes yearly groundwater extractions, electrical conductivity measurements, chemical analysis, and water-level measurements [48]. In 2012, the Regional Strategic Action Program for the Nubian Sandstone Aquifer System was negotiated through the Action Programme for the Integrated Management of the Shared Nubian Aquifer, which included guidance for future groundwater management agreements [18,53]. The JASD-NSAS has a regional expert group, with offices in each of the countries sharing the aquifer, as well as specific units for public relations, follow-up, finance, technical affairs, information, and administration.

3.2.6. Al-Saq/Al-Disi Aquifer System

The Al-Saq/Al-Disi Aquifer is a reservoir of fossil water shared by Jordan (Al-Saq Aquifer) and Saudi Arabia (Al-Disi Aquifer). Groundwater recharge in the region is minimal, and the two countries seem to be involved in a pumping race that might lead to the inevitable depletion of the groundwater resource [54]. The Agreement between the Government of the Hashemite Kingdom of Jordan and the Government of the Kingdom of Saudi Arabia for the Management and Utilization of the Ground Waters in the Al-Saq/Al-Disi Layer was signed on 4 April, 2015. The Al-Saq/Al-Disi Aquifer area covered by the agreement has an area extent of 308,000 km² [55].

The agreement restricts groundwater extractions in protected areas, encourages the drilling of observation wells, and includes pollution control statements. The agreement authorizes the drilling of wells in the management area between Jordan and Saudi Arabia but limits water usage for municipal purposes. A joint Saudi/Jordanian technical committee formed by five members from each country is responsible for supervising the implementation of the terms of the agreement, monitoring groundwater quality and quantity, and exchanging data and information between the involved parties. The agreement calls for members of the joint committee to have one meeting every six months. However, it was reported that as of 2018, the committee has never met [50]. According to the agreement, data exchange with a third party is not allowed unless approved by the two countries. Activities by the joint committee can be completed with the help of experts, technicians, officials, and citizens from the two countries. The agreement will be reviewed every 25 years, and any amendment will be studied by the joint committee and referred to the appropriate authorities. In this case, informal political meetings contributed to the development and signing of the MOU in 2015 [36]. However, the countries have not truly reached a bilateral treaty over the use of their shared groundwater [36].

3.3. *Transboundary Groundwater Collaboration between the United States and Mexico*

The allocation of shared surface water resources between the United States and Mexico is governed by the 1944 Water Treaty Regarding the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (1944 Treaty). The treaty, however, leaves groundwater unmentioned. The IBWC, established in 1889, is the international body that oversees the application of U.S.-Mexico treaties regarding boundary demarcation, water resources, and sanitation in the border region [12]. It received the name of the International Boundary Commission (IBC) before the signing of the 1944 Treaty.

The IBWC is composed of the U.S. and a Mexican Section. The U.S. Section is housed in the U.S. Department of State and has headquarters in El Paso, Texas. The Mexican Section is operated by the Mexican Ministry of Foreign Affairs, with headquarters in Ciudad Juárez, Chihuahua. To implement international treaty provisions, the IBWC requires specific agreements, which have been recorded in the form of Minutes and date back to 1889. A key pillar of the 1944 Treaty is that it allows for interpretations or modifications (Minutes) to adapt to new challenges that emerge between the two countries [56]. These Minutes are considered extensions and applications of the treaty [56]. To date, 324 Minutes act as binding obligations between the United States and Mexico, but only Minute 242 for the “Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River” specifically includes groundwater management provisions [57]. Resolution 5 of Minute 242 establishes that “pending the conclusion by the Governments of the United States and Mexico of a comprehensive agreement on groundwater in the border areas, each country shall limit pumping of groundwater in its territory within eight kilometers of the Arizona-Sonora boundary near San Luis to 197,358,000 cubic meters annually” [57]. Minute 323, “Extension of Cooperative Measures and Adoption of a Binational Water Scarcity Contingency Plan in the Colorado River Basin,” is a relevant example of cooperation for many reasons, including the assessment of desalination impacts [58]. While this Minute does not consider groundwater, it does consider a binational assessment effort within the context of the IBWC and the 1944 Treaty.

Aside from the 1944 Treaty framework, the Bellagio Draft Treaty represents another fine example of the progress being made toward the understanding and management of the U.S.-Mexico transboundary aquifers [16]. The treaty suggests a structure by which the United States and Mexico can work cooperatively, describing the development of a bilateral institution that will allow the United States and Mexico to jointly study and manage their shared groundwater resources [59]. Moreover, it emphasizes the importance of knowledge improvement for the development of joint agreements and the management of groundwater resources. Another collaborative effort between the United States and Mexico, the MOU between Ciudad Juárez Water Utilities and El Paso Water Utilities promotes the exchange of information and the development of binational studies in the region [18,47]. This surface-water and groundwater assessment effort represents a local approach arranged by interested communities [11], indicating the presence of different paths toward scientific groundwater collaboration on a local or regional scale.

Finally, the TAAP Cooperative Framework represents another mechanism of binational collaboration between the United States and Mexico. The knowledge-improvement goals included in the TAAP Cooperative Framework coincide with the data-collection efforts and assessment of shared water resources described in the Bellagio Draft Treaty of 1989. The TAAP Cooperative Framework is described below.

3.4. *The United States-Mexico Transboundary Aquifer Assessment Program*

Recognizing the interest of the United States and Mexico to understand their shared aquifers, and with U.S. Public Law 109-448 as a precedent, the Principal Engineers of the U.S. and Mexican sections of the IBWC signed the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program (TAAP Cooperative Framework) in August 2009. While some scholars argue that TAAP marginalizes issues such as

water rights and management [60], others have contended that improving understanding of the U.S.-Mexico transboundary aquifers, which is the objective of the TAAP Cooperative Framework, is a necessary first step toward a binational groundwater management agreement between the United States and Mexico [19].

The TAAP Cooperative Framework promotes the development of binational technical groups to evaluate shared aquifers, advocates for knowledge improvement and data exchange, and states that each country has an obligation to cooperate [24]. It is worth noting that these principles correspond to UN Draft Articles 7 and 8, “General Obligation to Cooperate” and “Regular Exchange of Data and Information” [19]. Additionally, TAAP principle 4 considers the sovereignty of each nation by stating, “no provision set forth [in this agreement] will limit what either country can do independently in its own territory.” This principle is consistent with UN Draft Article 3, “Sovereignty of Aquifer States” or countries that share the aquifer. UN Draft Article 13, regarding monitoring, is also consistent with the overall TAAP objective of improving knowledge of transboundary aquifer conditions.

Accomplishments of the TAAP include the development of the Mesilla Valley Hydrologic Model; the completion of the Binational Study of the Transboundary San Pedro Aquifer; the establishment of research projects in Texas, New Mexico, Arizona, Sonora, and Chihuahua; the output of numerous publications and conference presentations; and fieldwork in the U.S. and Mexican portions of the priority aquifers [61]. Additionally, over 50 binational meetings have taken place, many of them were between the technical workgroups established pursuant to the Cooperative Framework.

An existent legal mechanism for collaboration, regional institutions, funding mechanisms, high institutional capacity, previous water cooperation, and scientific research are some of the enabling mechanisms for groundwater collaboration that are present in the TAAP collaboration and that might facilitate future groundwater collaboration between the two countries.

3.4.1. Common Elements of Collaboration between the TAAP Cooperative Framework and International Aquifer Agreements

A comparison of the elements of the TAAP Cooperative Framework and the components of the six international groundwater agreements is presented in Table 3. Five items were particularly relevant as common features of collaboration: (1) the presence of data exchange provisions, which was true for all the agreements but the Al-Saq/Al-Disi Aquifer System; (2) the concurrence for binational aquifer assessment, agreed on and implemented by all the countries sharing an aquifer; (3) the establishment of technical advisory committees, which occurred in all of the countries; (4) the presence of technical groups, discussed in every agreement except the Bamako Declaration, and; (5) respect for the legal framework and jurisdictional requirements of each country, which was inferred from the content of each of the agreements and which apply to all of the analyzed aquifers.

These features of collaboration, present in all of the agreements except the Al-Saq/Al-Disi Aquifer System and the Iullemeden Aquifer, are in alignment with the main objective of the TAAP Cooperative Framework, which is to improve knowledge of transboundary aquifers. These features also demonstrate that groundwater assessment is necessary for managing transboundary aquifers. A notable difference between the agreements and the TAAP Cooperative Framework is the use of information. While the data generated through the TAAP serve only to improve knowledge, as do the data generated for the NSAS and the NSA, the information and monitoring outcomes from the GAS, Franco-Swiss Genevese Aquifer, Al-Saq/Al-Disi Aquifer System, and Iullemeden Aquifer can be used for decision-making purposes with respect to groundwater management.

Table 3. Common elements of collaboration between transboundary groundwater agreements (✓ = Component present in the agreement, ✗ = component absent in the agreement, * = inferred present component, ? = unspecified component, not shown in the agreement and cannot be inferred from additional content).

Elements of Collaboration		TAAP	GAS	Franco-Swiss Genevese	Northwest- ern Saharan	Iul- lmeden	NAS	Al-Saq/Al- Disi
Objectives	Exchange data	✓	✓	✓	✓	✓	✓	✗
	Concur on binational aquifer assessment activities	✓	✓	✓	✓	✓	✓	✓
	Establish and coordinate technical advisory committees	✓	✓	✓	✓	✓*	✓	✓
	Establish an official repository for binational project reports	✓	?	?	✓	?	?	✗
Framework (Process)	Establish technical groups	✓	✓	✓	✓	✗	✓	✓
	Develop project progress reports	✓	✓	✓	✓	?	✓	✓
	Publish final reports	✓	?	✓	✓	?	✓	✗
Funding	Arranged between the parties	✓	?	✓	✓	?	?	?
Principles	Activities should be beneficial to both countries	✓	✓*	✓*	✓*	✓*	✓*	✓*
	Activities should be agreed on within the framework of the coordinating agency	✓	?	?	?	?	?	?
	Activities should respect the legal framework and jurisdictional requirements of each country	✓	✓	✓	✓	✓	✓	✓
	No provision set forth in this agreement will limit what either country can do independently in its own territory	✓	✓	✓	✓	?	✓	✗
	No part of this agreement may contravene what has been stipulated in the Boundary and Water Treaties	✓	✓	✓	✓	?	✓	✓
	The information generated from these projects is solely for the purpose of expanding knowledge	✓	✗	✗	✓	✗	✓	✗
	An official repository of records will be present	✓	?	?	✓	?	?	✗
Communi- cation	Reports will be available to the public in each country	✓	?	✓	✓	?	✓	✗
	Information obtained will be considered official data and will be shared without any restrictions	✓	?	✓	✓	?	✓	✗
	Credit will be given to those who provide information	✓	✓*	✓*	✓*	✓*	✓*	?
		✓	✓*	✓*	✓*	✓*	✓*	?

Another difference between the agreements and the TAAP Cooperative Framework is the availability of aquifer assessment data to the public, which is not discussed by or does not apply to the rest of the transboundary aquifers. The IBWC is the official repository of the available studies, which are published in both English and Spanish through the organization's official website. The financial arrangements, as described in the TAAP Cooperative Framework, were rather uncommon, being present in the Franco-Swiss Genevese and the Northwestern Saharan Aquifer agreements only.

3.4.2. Expert Interviews on U.S.-Mexico Transboundary Groundwaters

Expert interviews on transboundary groundwater served to determine whether the TAAP principles of agreement could guide transboundary aquifer assessment in areas that have not entered into formal agreements for binational collaborative studies, ultimately leading to the development of groundwater management arrangements or agreements (Table 4).

Table 4. Summary of expert interview responses.

Question	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5	Interviewee 6
According to your experience, what factors promote the successful groundwater collaboration between nations that share one or various aquifers?	<ul style="list-style-type: none"> -Interest -Compliance with existing agreements -Respect for cultural differences -Consideration for institutional asymmetries 	<ul style="list-style-type: none"> -Friendly relations between countries -Pre-existing framework for collaboration 	<ul style="list-style-type: none"> -Pre-existing institutional framework -Data-sharing mechanisms -Trust -Interest -Funding 	<ul style="list-style-type: none"> -Trust -Considering imbalances between countries -Processes that promote trust, e.g., data sharing and prior notification -Avoiding water-right discussions in the initial stages 	<ul style="list-style-type: none"> -Trust -Common issues/problems -People—not institutions—promoting cooperation 	<ul style="list-style-type: none"> -Local agreements -Avoiding water-right discussions -Focusing on water quality
<p>Do you think we can generalize the TAAP principles of collaboration and apply them to other aquifers within the U.S.-Mexico border?</p> <p>Do you think the TAAP Cooperative Framework can serve as a model for the assessment of other transboundary aquifers?</p>	<ul style="list-style-type: none"> -General principles can be utilized -Take into account the uniqueness of each aquifer system 	<ul style="list-style-type: none"> -Principles can help other countries deal with the use of shared groundwater resources -Absolute commitment is needed between countries 	<ul style="list-style-type: none"> -Important model to consider in countries with or without pre-existing frameworks for collaboration -Depends on the circumstances -Require higher-level discussions -Partnerships among universities, federal agencies, and coordinating agencies provide a favorable model 	<ul style="list-style-type: none"> -Follow the basic rules of cooperation and apply them to the specific needs of each aquifer 	-	<ul style="list-style-type: none"> -Elements are good but worked due to the leadership of specific members -Does not have federal strength -Political sensitivity limits data sharing -Formality of relations slows down collaboration
Do you think the TAAP Cooperative Framework can serve as a basis for the development of future groundwater management agreements in the borderlands of the United States and Mexico?	<ul style="list-style-type: none"> -Principles can serve as a foundation -There has to be a reason/interest that drives the development of a groundwater agreement 	<ul style="list-style-type: none"> -Smaller, localized agreements are needed -States should be involved 	<ul style="list-style-type: none"> -A framework for talking about groundwater management is needed 	<ul style="list-style-type: none"> -A generic framework for collaboration is needed -You can implement a framework for the whole border stating that each aquifer must have its own regime 	<ul style="list-style-type: none"> -I don't think so -Water management differs greatly between the borderlands 	<ul style="list-style-type: none"> -Not as it stands right now -Does not help to plan, manage, or learn about the border -It is limited to only four aquifers

Interviewees reported that the TAAP principles are general enough to be used as a guide to promoting additional groundwater collaboration for the assessment of other transboundary aquifers in the United States and Mexico. This can be supported by a statement included within the TAAP Cooperative Framework (framework/processes): “Either of the two countries can propose an aquifer to study. Within the IBWC framework, it will be determined whether the proposal is in common interest and, as appropriate, a joint program developed.” However, the commitment of the involved countries must be “absolute”; i.e., the time frame, funding, and political support for the analysis should be established between the collaborating parties. Participants also commented that because the TAAP effort involves partnerships among universities, federal agencies, and coordinating agencies, it provides a favorable model for collaboration. Nevertheless, its application

would depend on the circumstances of each partner country and also on the leadership of the involved members. Historic or high levels of distrust between the two countries may interfere with the process of collaboration, while a pre-existing foundation, as demonstrated by the 1944 Treaty and the IBWC Framework in the case of Mexico, has facilitated collaboration. On the other hand, it was also expressed that even though the elements of the TAAP Cooperative Framework are effective, it lacks a binding capacity and federal and institutional support from both the United States and Mexico, a fact that sometimes hinders cooperation between the two nations.

Regarding the development of transboundary groundwater management agreements between the United States and Mexico, interviewees stated that the uniqueness of each aquifer system might require the development of aquifer-specific agreements. It was also expressed that the TAAP Cooperative Framework, as it stands right now, cannot serve as the foundation for groundwater management agreements due to the differences in water management between the United States and Mexico. An alternative proposed during the interview process was the possible development of a regional agreement for the use of groundwater resources in the border region. Such an agreement could employ principles of the TAAP Cooperative Framework, and it should be consistent with the UN Draft Articles and existing international groundwater agreements, as well. According to the interviews, the case of aquifer-specific agreements will require the direct involvement of each of the individual states, due to the decentralized way in which water resources are managed in the United States. Each state within U.S. territory has different needs, goals, funds, and management schemes; therefore, each state must play an active role in the development of an agreement.

Interviewees expressed that trust is a key factor in successful groundwater collaboration and that data sharing processes can improve trust between different countries. The interest between involved parties and common issues can also promote collaboration. Respect for cultural differences, institutional asymmetries, and economic imbalance is essential. Finally, additional indicators of successful groundwater collaboration include the presence of a pre-existing institutional framework and the countries' compliance with pre-existing agreements.

3.4.3. The TAAP Cooperative Framework as a Model for Groundwater Collaboration

The TAAP is a binational scientific effort that enabled groundwater data exchange and harmonization, knowledge improvement of the TAAP aquifers of focus, and trust-building among the federal agencies, academic institutions, and water resources research institutes that collaborated in the program. It was enabled by a governance approach, the Joint Report of the Principal Engineers Regarding Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program of 2009, and, for the United States, the TAA-Act of 2006 (Figure 2). The TAAP history of collaboration exhibits six out of eight enabling factors for groundwater collaboration described in the current literature [18]: (1) a strong regional institution like the IBWC (U.S. and Mexican Section); (2) existing legal mechanisms, such as the 1944 Treaty and the IBWC Minutes; (3) previous water collaboration for solving water-related issues; (4) third-party involvement from entities that do not belong to the government of each country, such as academic institutions; (5) scientific research on transboundary aquifers, and; (6) funding mechanisms (Figure 2). Although the two remaining features, high institutional capacity, and strong political will are not fully present in the TAAP, they are not absent either. Strong political will is identified when high-ranking officials prioritize transboundary water management [18]. However, the facilitation of diplomatic events and meetings like the ones hosted by the IBWC and TAAP can be considered an early sign for the strengthening of political will. The monitoring and modeling efforts that are present in the TAAP can also be considered factors that strengthen institutional capacity.

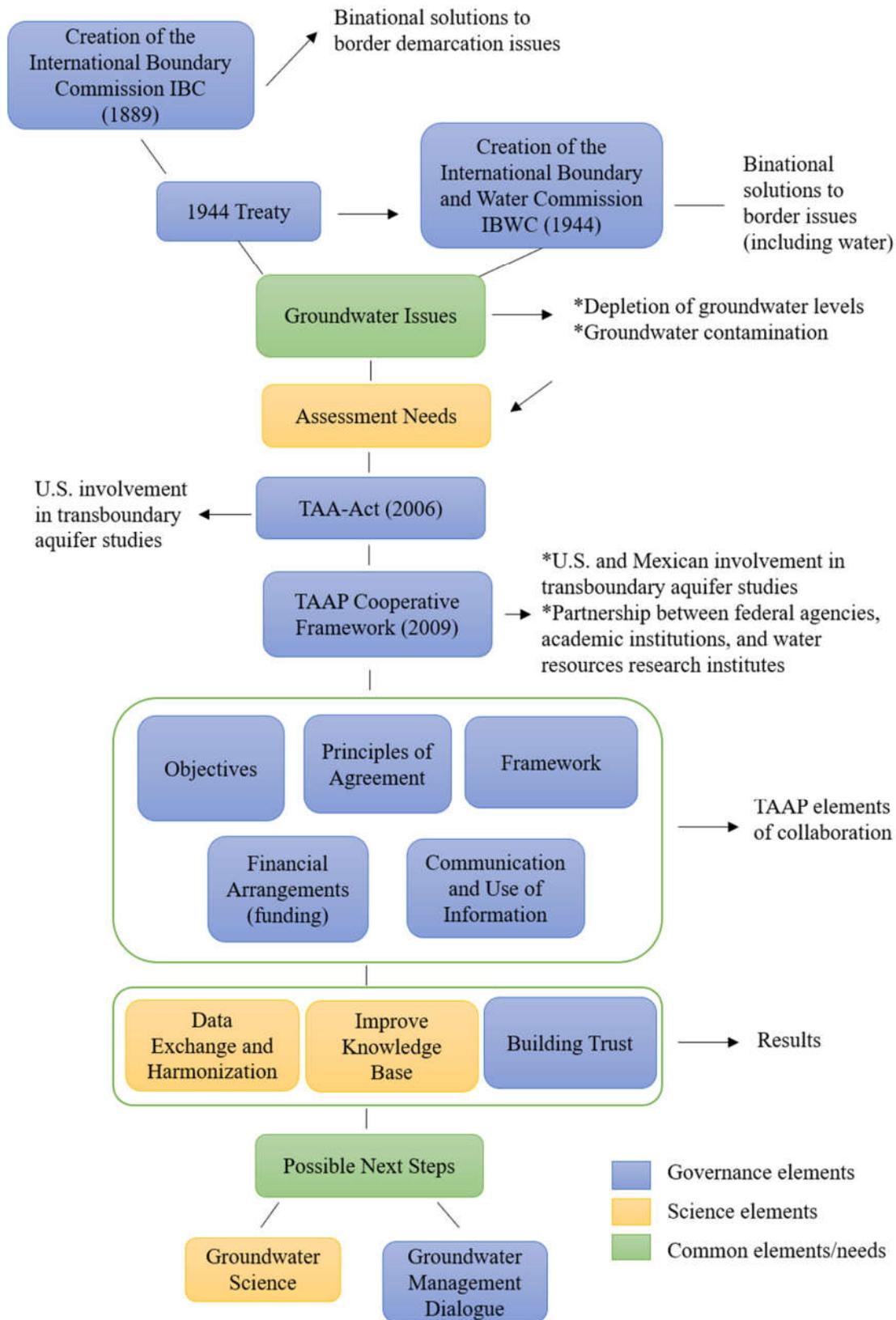


Figure 2. Evolution of the United States-Mexico Transboundary Aquifer Assessment Program.

The TAAP represents a pre-existing institutional arrangement that promotes trust development between the United States and Mexico, in addition to the development of groundwater assessment studies within the aquifers of focus. These outcomes position the two countries to move forward in one of two ways: (1) implement additional assessment within the transboundary aquifers shared by the United States and Mexico, or (2) initiate dialogue toward the need of developing groundwater management mechanisms for the two countries. While a dialog is needed between the United States and Mexico to determine the need for a possible groundwater management agreement and the scale of the agreement itself, the importance of considering the unique physical, cultural, institutional, and economic characteristics surrounding specific aquifers is essential, as expressed during the expert interviews.

The analysis of common elements of collaboration between existing groundwater cooperation mechanisms and the TAAP indicates that the program itself, which is guided by the TAAP Cooperative Framework, has laid the groundwork for the development of additional aquifer assessment studies along the U.S.-Mexico border. The principles contained within the framework, which already include the majority of the elements described in pre-existing aquifer agreements, allow the two countries to continue studying additional aquifers and help to build trust between the involved parties (Figure 2). Moreover, the TAAP encompasses tenets such as communication and funding principles not previously mentioned in other aquifer agreements. These statements support the fact that the TAAP Cooperative Framework can be used as a model for transborder groundwater collaboration for the assessment of transboundary aquifers between the United States and Mexico and around the world.

4. Discussion

Currently, there is no groundwater treaty between the United States and Mexico. The 1944 Water Treaty regarding the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (1944 Treaty) is the primary surface-water-allocating mechanism for the two countries. The treaty, however, does not mention groundwater. The Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program (TAAP Cooperative Framework) is a case of groundwater collaboration for the assessment of the U.S.-Mexico transboundary aquifers of focus: the Santa Cruz, San Pedro, Mesilla, and Hueco Bolson aquifers. However, at least 36 transboundary aquifers shared by the United States and Mexico have been identified so far [25].

Relevant studies on U.S.-Mexico groundwater governance have analyzed (1) the intranational institutions for the management of shared groundwater resources [22]; (2) the importance of institutional asymmetries for transboundary aquifer assessment [20]; (3) the institutional assessment of the Transboundary Santa Cruz and San Pedro Aquifers [21], and; (4) the management perspectives for the shared aquifers of the United States and Mexico [25]. While most of these studies discussed the outcomes, advantages, and disadvantages of the TAAP Cooperative Framework and the program itself, the components of the TAAP Cooperative Framework have not been analyzed as a model for groundwater collaboration.

This study analyzed the TAAP Cooperative Framework as a guide for furthering scientific assessment in areas that have not entered into formal agreements for binational collaborative studies. Through literature review and analysis of existing transboundary groundwater management agreements, we found that common elements of collaboration between the TAAP Cooperative Framework and existing groundwater management agreements include provisions for the exchange of data, concurrence for binational aquifer assessment, the establishment of technical advisory committees and technical groups, and respect for the legal framework and jurisdictional requirements of each country.

The TAAP exhibits several features that enable groundwater collaboration: existing legal mechanisms, previous water collaboration, third-party involvement, scientific research, and funding mechanisms. Additionally, the framework is consistent with four UN Draft Articles on the Law of Transboundary Aquifers, findings that may indicate the readiness of the two countries to move on to a next step: to implement additional aquifer assessment along the U.S.-Mexico border or to initiate dialogue toward the development of groundwater management mechanisms.

Some scholars have argued that the TAAP marginalizes issues such as groundwater rights and management [60] and lacks a binding capacity (personal communication, 2020), and we agree with this premise. The information generated through the TAAP is “solely for the purpose of expanding knowledge” [20]. However, the present study has found that scientific assessment is a prior step for the development of groundwater management agreements. In fact, interviews with experts on transboundary waters explored two ways in which the TAAP could guide groundwater management: through local agreements for the management of specific aquifer systems or through a regional agreement that guides the use of groundwater resources in the border region. In any case, lessons from the TAAP Cooperative Framework and the program itself remain as a model of robust binational groundwater collaboration with principles that have the potential to guide future groundwater assessment and management not just along the U.S.-Mexico border, but across the world.

5. Conclusions

The United States and Mexico share rivers, basins, and aquifers. Yet they do not share a water management agreement that suits the needs of the border communities that completely rely on groundwater resources. Challenges for managing shared groundwater in the region include population growth, industrialization, increase in agriculture, contamination, increase in surface water and groundwater demands, and climate uncertainties. These challenges indicate that some sort of binational arrangement is needed to protect and manage the shared groundwater resources. However, the topic has only been mentioned twice since the IBWC was created. Almost five decades after the signing of Minute 242 and three decades after the development of the Bellagio Draft Treaty, there has been no effort to establish a comprehensive groundwater agreement. Meanwhile, efforts toward increasing understanding of the U.S.-Mexico transboundary aquifers have taken place. This study analyzed the TAAP Cooperative Framework as a guide for furthering scientific assessment in areas that have not entered into formal agreements for binational collaborative studies. To achieve this, we compared the elements of collaboration present within the TAAP Cooperative Framework and six transboundary aquifer agreements around the world.

From this analysis, we found that five elements were particularly relevant as common features of collaboration that align with the TAAP Cooperative Framework: (1) the presence of data exchange provisions, (2) the concurrence for binational aquifer assessment, (3) the establishment of technical advisory committees, which occurred with all of the aquifers, (4) the presence of technical groups, and (5) respect for the legal framework and jurisdictional requirements of the involved countries. Expert interviews also served to identify lessons learned from the TAAP and global challenges for groundwater collaboration, which included the importance of trust-building between border communities sharing water resources, groundwater assessment, and a pre-existing framework for collaboration. It was also suggested that the TAAP principles are general enough to be used as a guide to promoting additional groundwater collaboration for the assessment of other transboundary aquifers in Mexico and the United States and around the world. Yet, the applicability of the TAAP Cooperative Framework will depend largely on the unique circumstances of the involved countries.

We conclude for several reasons that the transboundary aquifer assessment efforts following the TAAP Cooperative Framework represent a model for others wishing to engage in transboundary aquifer assessment. The TAAP Cooperative Framework is a concisely written and readily available document that has been successfully approved and signed by two countries. It has promoted productive scientific collaboration between the United States and Mexico in a manner consistent with the Draft Articles on the Law of Transboundary Aquifers (UN Draft Articles). Its elements are also consistent with the information gathering portion of successful groundwater management agreements around the world. It includes funding and communication provisions that are uncommon in existing international agreements but that facilitate groundwater cooperation, as made evident by the collaboration to date. Finally, according to the TAAP Cooperative Framework, either of the two countries can propose an aquifer of focus, meaning that there is no need to develop a new cooperative framework for assessing additional transboundary aquifers shared by the United States and Mexico.

The present study finds evidence of successful outcomes within the TAAP Cooperative Framework consistent with available transboundary groundwater management agreements, demonstrating that the approach is suited to serve as a model for others wishing to engage in transborder aquifer assessments worldwide. Furthermore, the principles of the TAAP Cooperative Framework include elements that promote trust between the United States and Mexico (e.g., data sharing, development of binational aquifer assessment activities, the establishment of technical advisory committees, and establishment of technical groups). These and the rest of the TAAP elements of collaboration can help to establish the meaningful and robust binational cooperation necessary for the development of U.S.-Mexico groundwater management agreements at the aquifer level.

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