

## Article

# Science and Binational Cooperation: Bidirectionality in the Transboundary Aquifer Assessment Program in the Arizona-Sonora Border Region

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**Abstract:** Sharing scientific data and information is often cited within academic literature as an initial step of water cooperation, but the transfer of research findings into policy and practice is often slow and inconsistent. Certain attributes—including salience, credibility, and legitimacy of scientific information; iterative information production; and sociocultural factors—may influence how easily scientific information can be used in management and policymaking. However, transnationality usually complicates these sorts of interactions. Accordingly, we argue that the production of scientific information and transboundary water cooperation build upon each other *bidirectionally*, each informing and enhancing the other. We employ a case-study analysis of the Transboundary Aquifer Assessment Program (TAAP), a binational collaborative effort for scientific assessment of aquifers shared between Mexico and the United States. Here, information sharing was possible only by first completing a formal, jointly agreed-upon cooperative framework in 2009. This framework resulted in a collaborative science production process, suggesting that the relationship between sharing data and information and transboundary groundwater governance is iterative and self-reinforcing. In keeping with the publication of the TAAP's first binational scientific report in 2016, we demonstrate the bidirectional relationship between science production and water governance in the TAAP and explore remaining challenges after scientific assessment.

**Keywords:** transboundary waters; groundwater; US–Mexico; water governance; science production; bidirectionality



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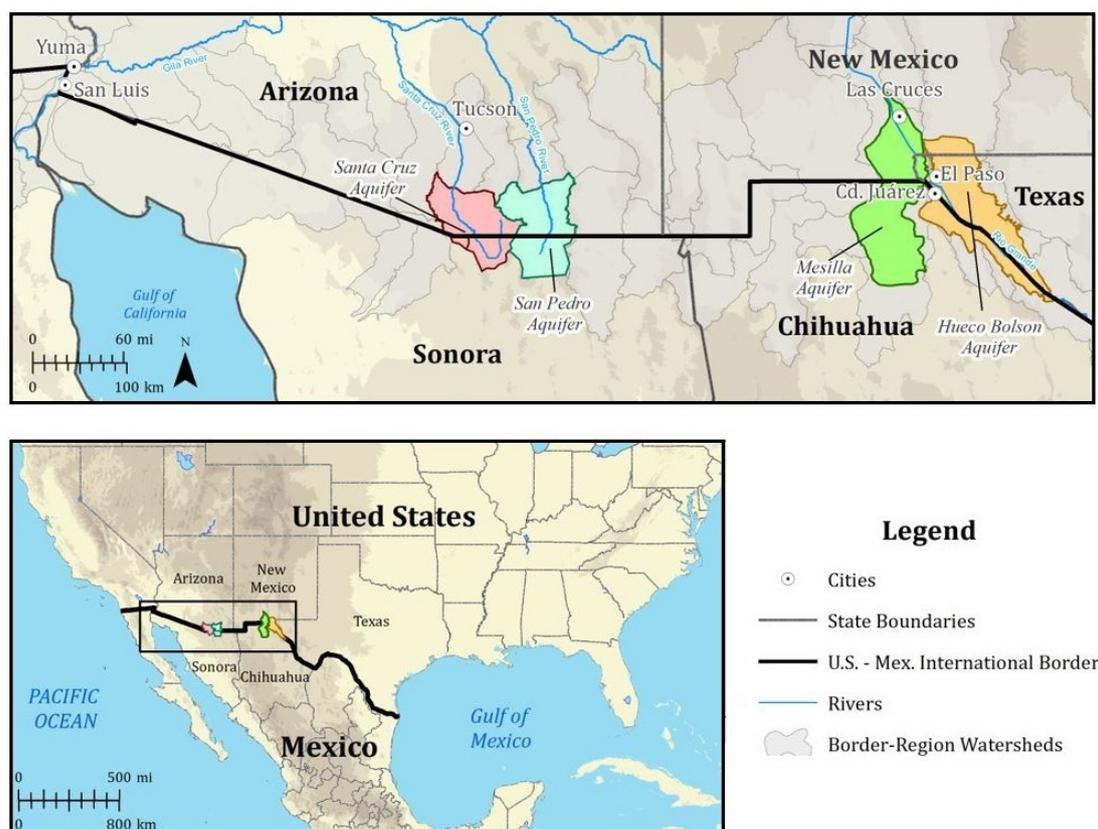
## 1. Introduction

The arid to semiarid region of the southwestern United States (US) and northwestern Mexico is water-short in most of its geographical reach. Climate-change predictions indicate rising temperatures and increased variability in precipitation patterns, leading to water supply reductions by the middle of the 21st century [1–3]. This hydrological variability affects groundwater basins; the southwestern US is likely to experience declines in groundwater recharge, including in basins such as the San Pedro [4] and Santa Cruz [5,6].

Mexico and the US share four river basins (Tijuana, Colorado, Yaqui, and Rio Grande/Rio Bravo). The two that are by far the largest, the Colorado and Rio Grande/Rio Bravo basins, encompass almost the entirety of the border region. Additionally, 36 aquifers have been identified along the Mexico–US border; 16 of these can be categorized as transbound-ary [7]. Yet, while surface-water agreements govern and manage the binational Tijuana,

Colorado, and Rio Grande/Rio Bravo river basins, there exists no formal agreement on management of any of the transboundary aquifers.

The absence of binational/multinational transboundary institutions governing internationally shared groundwater is typical among almost all transboundary aquifers. Globally, for the almost 600 identified aquifers crossing international boundaries [8], only a handful of formal agreements over transboundary groundwater exist [9,10], even in locations that exhibit high levels of cooperation regarding other issues. Developing a shared understanding is a prerequisite to joint management of a resource, most especially an unseen one. The US and Mexico have cooperated scientifically—though not managerially—to assess four of their shared aquifers: the San Pedro and Santa Cruz, shared between Sonora (Mexico) and Arizona (US), and the Mesilla–Conejos Medanos and Hueco Bolson, shared among three subfederal entities: the Mexican state of Chihuahua, and the US states of New Mexico and Texas (Figure 1).



**Figure 1.** TAAP's aquifers of focus on the Mexico–US border.

Transboundary water resources—whether above or below the surface—span a border and are shared. Here we highlight that the information, interpretation, science, and actions that are needed to manage those resources flow both ways across the border in question. Our aim is to show that the relationship between science production and groundwater governance is bidirectional, with institutions in both countries exerting influence on the outcomes.

The paper seeks to analyze the case study using process tracing ([11]; see, e.g., [12,13]). We argue that analyzing the two-way flow of science production and cooperative governance (e.g., [14]) has yet to be adequately explored in transboundary groundwater governance literature. Specifically, we look at how these processes enhance each other in the Transboundary Aquifer Assessment Program (TAAP) aquifers of focus (Figure 1) shared between Arizona and Sonora—the Santa Cruz and San Pedro aquifers.

First, looking at one direction of the flow, we examine how national and binational policies and cooperative actions, spearheaded by university and government agency research partnerships on both sides of the border, led to advancements in scientific knowledge. The most notable of those advancements was the completion of the first-ever binational scientific aquifer assessments, prepared and released simultaneously in English and Spanish by the (US–Mexico) International Boundary and Water Commission (IBWC). The IBWC/CILA (Comisión Internacional de Límites y Aguas; the Mexican name of the commission) is the binational organization whose mission is “to provide binational solutions to issues that arise during the application of US–Mexico treaties regarding boundary demarcation, national ownership of waters, sanitation, water quality, and flood control in the border region” [15].

Then, viewing the other direction, we discuss how data and information resulting from assessments may contribute to future decision-making for shared groundwater in the border region.

In the following sections, we explore principles of water governance and, specifically, which factors enhance cooperation in groundwater governance. As part of the process, we also examine the role of science in informing policymaking. Next, we use the outlined principles of water governance to analyze how elements of the science–policy interface relate to groundwater governance in the case of the TAAP in Arizona and Sonora.

## 2. Literature Review

While the science–policy interface has been addressed in water management generally (e.g., [16,17]) and transboundary water management specifically (e.g., [18]), little has been written describing which elements of water governance need to be present for coproduction of knowledge to occur in a transboundary setting (Armitage et al. [19] being a notable exception). Acknowledging that our selection of key principles for the science–policy interface in transboundary groundwater governance is not exhaustive, we review frequently identified principles for analyzing groundwater governance and the science–policy interface in the following paragraphs.

### 2.1. Principles for Analyzing Groundwater Governance

Though governmental entities are more likely to be cooperative than conflictive over shared waters [20], there exist certain factors that make it easier—or more difficult—for cooperation to occur. Among the barriers to transboundary cooperation are spatial and social distance [21–24]; limitations in institutional capacity, financial resources, participation capacity, and data availability [25]; layering and asymmetries of governance structures [26] and intrajurisdictional integration within countries [27,28]; incompatible governance cultures and mandates; and mistrust and/or lack of leadership [25]. Here, social distance refers to disparities in cultural, ethnic, religious, linguistic, political, administrative, legal, and traditional ways of managing and governing water resources. These and other potential asymmetries complicate transboundary resources management. Drivers for transboundary cooperation include leadership, personal relationships, contacts, the existence of binational (or multinational) institutions, and functioning networks [25].

When initiating cooperation on international waters, the chances of such cooperation being successful increase when autonomies of each party are respected, basinwide networks of scientists are established, diverse groups of stakeholders are consulted, and perhaps above all, all parties establish and maintain trust [29]. Such cooperation encourages solving common problems and cultivates interdependence and mutual understanding [30].

Narrowing our focus to transboundary groundwater, scholars have recognized the underdeveloped and/or fragmented structures for resolving critical problems in groundwater governance [10,31–34]. Here, we define groundwater governance as “the overarching framework of groundwater use laws, regulations, and customs, as well as the processes of engaging the public sector, the private sector, and civil society ([35]; p. 678). Cooperation is a key element in transboundary aquifer governance. Enabling factors include: existing le-

gal mechanisms, functioning regional institutions, funding mechanisms, high institutional capacity, previous water cooperation, scientific research, and strong political will [36].

Several articles have identified elements, or “pillars,” of surface water and groundwater governance (e.g., [10,37–41]). Regarding groundwater, principles for management, planning, and assessment can be summarized as follows: *stakeholder engagement and inclusion, proper assessment and data for analysis, management and planning for groundwater use, integrated water management, and protection of groundwater resources* [10,38,39].

The reviews of groundwater governance principles and enabling factors presented here feature certain commonalities, including stakeholder engagement, management and planning, integrated water management, protecting groundwater resources, functioning institutional presence and capacity, history of water cooperation, funding, and political will. Other common factors are data sharing and scientific cooperation. Even low levels of scientific research can motivate some degree of cooperation [36], as that research can lead to increased transparency [42].

Complications associated with transboundary aquifers have been recognized for many years by scholars and intergovernmental organizations (e.g., [43,44]). Although few in number, formal international groundwater agreements vary in their legal nature, scope, status, content, duration, and driving motivation, and of course, degree of successful implementation [45]. This suggests that approaches to international groundwater problems are often site-specific and ad hoc in nature [21]. The few existing international groundwater agreements all contain some mechanism for data collection and/or exchange, and most also provide an institutional framework [45]. One of the most prominent such agreements addresses the Guaraní Aquifer in South America. The countries had to overcome asymmetries in political power and water governance structures (e.g., level of centralization) [46]. Despite the original promise of the accord, implementation has been a challenging process [47]. Jordan and Saudi Arabia also signed and ratified a bilateral (though not fully operational) agreement on the Disi Aquifer in 2015 [48] after exploitation from both countries, including withdrawals from a Jordanian pipeline project [49].

## 2.2. Analyzing the Science–Policy Interface in Transboundary Groundwater Governance

The bidirectional relationship between data-cum-information exchange and groundwater governance is a clear example of the science–policy interface. We define this interface to be how policy actors and scientists interact with each other through processes such as exchanging and joint constructing knowledge [50]. This building of place-based knowledge of groundwater resources is a key step toward effective management and governance [51]. In transboundary contexts, scientific assessment is a needed initial step to determine *whether* and *the extent to which* individual aquifers are cross-border physical systems (see [8,52]). Assessment can also help to catalog existing data sources and identify what data gaps exist. Such lacunae are common for transboundary aquifers because availability of and access to groundwater data are especially constrained [53], of uneven quality and reliability, and sometimes the result of disparate measurement systems and protocols [22].

Long-term planning for sustainable groundwater management also requires both characterization and ongoing monitoring due to the complexity and everchanging conditions of aquifer systems and inherent scientific uncertainty in groundwater evaluation. Management practices need to account for hydrogeological characteristics of transboundary aquifers via such strategies as pollution prevention, integrated land and water management, and context-specific approaches [39,54–56].

Certain attributes—such as salience, credibility, and legitimacy of scientific data and information—may determine how easily scientific information can be utilized in management and decision-making [57]. Salience (the relevance of information to decision-makers and/or the public; [57]) increases when the questions asked are relevant to the actors involved; it can be achieved through cooperative development of project goals via two-way communication [58,59]. Building trust and accountability via long-term relationships also bolsters salience, along with credibility (the creation of information that

is believable, trusted, and authoritative; [57]) and legitimacy of the process of knowledge production (the perception of how fair the knowledge production is, whether it includes different perspectives, and appropriate values and concerns; [57,60]). Involving actors perceived as experts in the task at hand tends to enhance credibility. However, if experts do not represent multiple points of view, or if the information is not produced via a transparent process, the data may not be perceived as fully legitimate. Legitimacy can be increased when scientific data are generated via cooperative, inclusive efforts, using mutually agreed-upon protocols. Conversely, lack of consensus on the instruments and methods used for data collection can impede cross-border cooperation [61]. Collaborative knowledge production and institutionalized science–policy processes that engage stakeholders—either via a cross-border organization or established network of stakeholders—can bolster the legitimacy of decision-making processes and knowledge generated in transboundary water contexts [19].

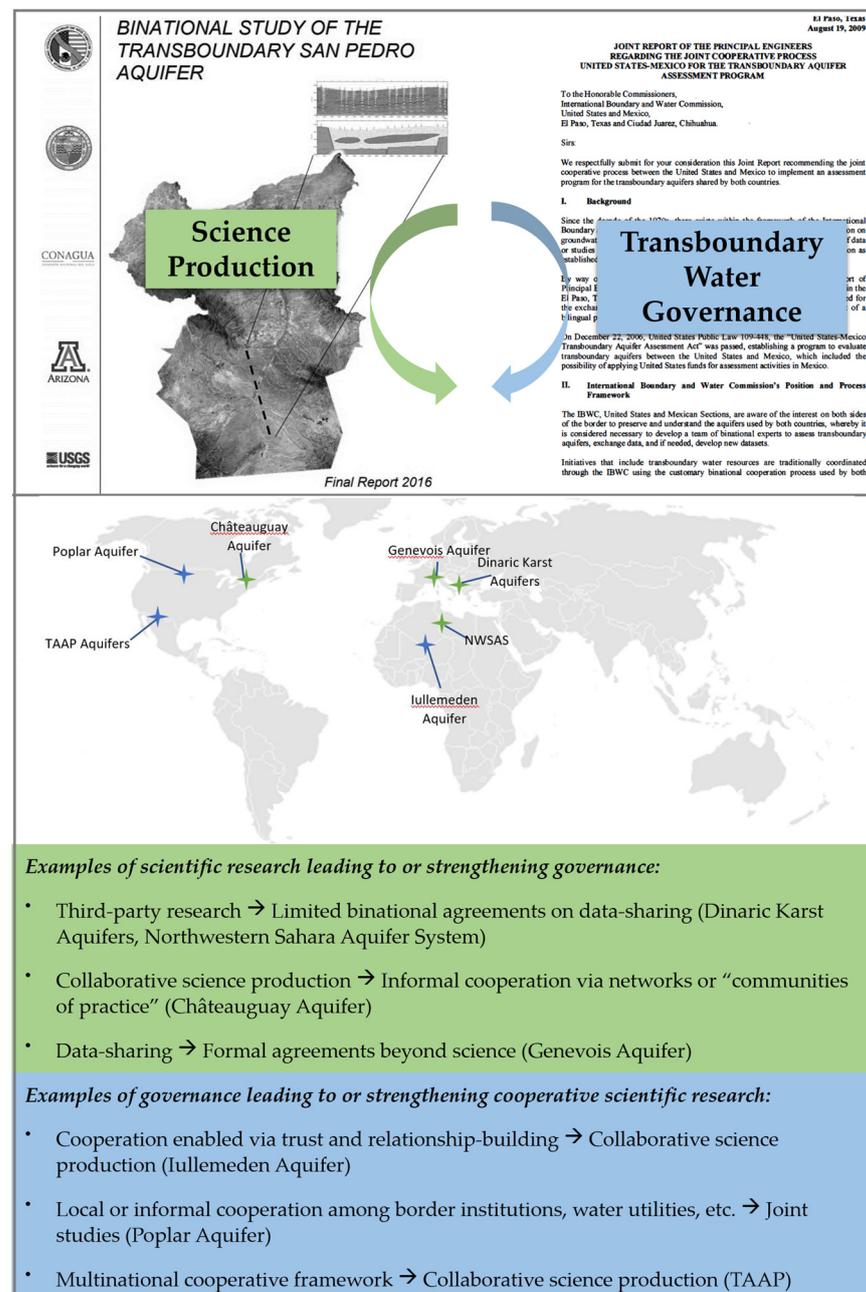
These science–policy processes may not necessarily yield deliberate progress toward some final state, but they do offer a developmental path from an initial state [62]. They may require iteration, building on previous practices, and learning from past successes and failures. Iterative processes are essential to positive science–policy interface outcomes, since capacity, trust building, and adaptability require multiple iterations [63–65]. Multiple iterations may also be necessary when new data or understanding is obtained [62,66].

In some cases, cross-border knowledge generation can provide a foundation for or promote further cooperation, such as formal agreements. Of the existing international agreements on shared groundwater, most were initiated by knowledge-generation efforts and/or from funding and assistance from international organizations [45]. Cooperation can be promoted via joint collection of high-quality data—thereby reducing the potential for data to be contested [67]. Joint monitoring, data collection, and data sharing are recognized as beginning steps within the cooperative process [68]. Joint studies of the Guaraní Aquifer System [47,69], the Nubian Sandstone Aquifer [70], and the Iullemeden Aquifer [69] are examples of this.

Yet in other cases, having prior cooperation or specific agreements in place can also help lead to improved scientific studies. Joint scientific studies may require a foundation of cooperative relations that could include transboundary institutional capacity, a framework for cooperation, or merely the presence of trust and prior working relationships. These studies on transboundary waters are often used to alleviate unidentified gaps in knowledge, missing information, data incompatibility, variation in quality control of data, and lack of scientific understandings [71]. Armitage et al. [19] describe the importance of setting the “conditions for collaboration” early on in transboundary science–policy processes by engaging relevant stakeholders, building relationships and bolstering trust. In both the Danube and the Orange–Senqu basins, for example, establishment of transboundary institutions—river basin organizations—made it possible to conduct cohesive basinwide water quality studies via collaborative studies involving all basin states in knowledge production [19]. Similarly, the US–Mexico agreement on the release of an environmental pulse flow in the Colorado River led to many new scientific discoveries [72].

When science is produced via collaborative processes that engage multiple parties, the information produced is more likely to be accepted by the participating countries. Science–policy processes for transboundary groundwater do not evolve the same way each time—the process is nuanced and involves give-and-take between progress toward scientific investigation and information gathering on the one hand, and political cooperation and agreements enabling people and organizations to work together on the other. Examples of how this critical bidirectional relationship between science and policy manifests in transboundary water governance is demonstrated in Figure 2.

Using the principles of good governance and role of science in decision-making outlined above, we turn now to analyze groundwater governance and processes of science production in one illustrative case: the implementation of the TAAP in Sonora and Arizona.



**Figure 2.** Bidirectionality of science production and transboundary water governance. Case study examples aside from the TAAP are from [69].

### 3. Materials and Methods

This paper employs a case-study method to investigate the relationship between science production and groundwater governance in the US–Mexico border region. Based on the results of our literature review above, we hypothesize the following:

**Hypothesis 1 (H1).** *Science contributes to and influences transboundary groundwater governance by informing management with a transboundary scientific understanding on both sides of the international border.*

**Hypothesis 2 (H2).** *Transboundary groundwater governance, through policies, agreements, and other cooperative efforts, contributes to and influences the course of scientific inquiry by expanding*

cooperative scientific networks across the border, including communities of practice. This in turn helps to generate new scientific knowledge that likely would not be possible without governmental cooperation.

To test these hypotheses, we employ both process tracing and interviews. First, we analyze elements that have been identified as enabling factors for good groundwater governance, as synthesized from the literature: stakeholder engagement and inclusion, management and planning for groundwater use, integrated water management, protecting groundwater resources, institutional presence and capacity, history of water cooperation, funding, and political will. “Good governance” suggests normative characteristics of being efficient, inclusive, and sustainable. Next, we use key features of scientific information that promote its ease of use in policymaking—salience, credibility, legitimacy [57], and iterative knowledge production [63,64]—to evaluate the bidirectional relationship of science and policy. Finally, we gathered data by conducting 20 interviews of government officials and scientists on both sides of the border (see Supplementary Materials, Table S1), participant observation, and by compiling secondary sources from binational technical meetings, conferences, and stakeholder meetings that took place during the 2010–2019 period.

We asked two sets of interview questions: one for scientists (Table S2), and one for government officials (Table S3). Questions for scientists focused on whether and how transboundary groundwater governance contributes to science by engaging relevant stakeholders, building relationships, and bolstering trust, thereby leading to scientific discoveries. Questions for government officials queried whether and how science (specifically groundwater assessment) contributes to groundwater governance.

#### 4. Results

The adjacent transboundary Santa Cruz and San Pedro aquifers are in southeastern Arizona and northeastern Sonora (Figure 3). Both aquifers support significant populations and economic activities such as mining, agriculture, ranching, tourism, and manufacturing. These aquifers have also seen rapid population growth in recent years [73,74].



**Figure 3.** The Santa Cruz and San Pedro aquifers.

##### 4.1. Water Management and Governance on Both Sides of the Border

Different modes and institutions for water governance between Mexico and the US complicate bilateral cooperation and assessment by making the transfer of information and

reaching consensus more challenging. Water management and governance in Mexico's nonborder waters tend to be more centralized than in the US [26]. The authority to regulate surface water and groundwater in Mexico resides with Comisión Nacional del Agua (CONAGUA), the national water authority. CONAGUA is responsible for all activities concerning use, management, and protection of national water. At the state and substate levels of government in Mexico, water management is more limited compared to the US; CEA Sonora (Comisión Estatal del Agua Sonora, Sonora's state water commission) assists municipalities in providing water and sanitation services and administers water supply-related programs, and certain municipalities run their own water and wastewater utilities [75].

Water management and governance in the US generally occur at the state and/or substate level. The federal government has built projects for flood control, transportation, hydropower dams, and large-scale water diversions [76] and has set water quality goals through measures such as the 1972 US Clean Water Act and the 1974 US Safe Drinking Water Act. States have authority over implementation of standards, practices, and rules for water use [77]. In Arizona, state law considers groundwater and surface water as distinct water bodies and are regulated as such. While surface water rights in Arizona are regulated under a *prior-appropriation system* ("first in time, first in right"), groundwater use is based on *beneficial use* (e.g., agricultural, industrial, or residential). Groundwater regulations vary across the state. Several regions of the state, including the US portion of the Santa Cruz Aquifer, are designated Active Management Areas (AMAs), where groundwater use is subject to regulations that are meant to be enforced by the Arizona Department of Water Resources [78,79]. As Figure 2 shows, the US portion of the binational San Pedro Aquifer is not part of an AMA.

#### 4.2. Binational Water Management

The 1944 treaty, "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande," gives the IBWC authority to make rules through adopting minutes (interpretations and clarifications) to the treaty. The IBWC has some authority in water shared between Mexico and the US to ensure compliance with the 1944 treaty, manage joint infrastructure, maintain hydrologic monitoring stations, and communicate information across the border [80]. This is due in part because Mexico's policy requires that all border groundwater (and surface water) issues be handled through the commission [81]. The IBWC comprises two sections, with one section in Mexico (CILA) and one in the US.

In the past century, Mexico and the US have expanded transboundary surface water governance capacity, moved towards inclusion of non-nation-state actors, increased ecological considerations, and have signed agreements related to surface water—most notably the 1944 treaty [82]. There exists no agreement over the management of shared groundwater aside from Minute 242, which addresses groundwater pumping near the US–Mexico border near San Luis, Mexico [83]. Minute 242 authorized the IBWC to begin discussions on a binational groundwater agreement [80], but little progress has been made to date. Issues surrounding water rights on both sides of the border, including those of private parties and concessionaires, remain unresolved [84]. There have also been notable disputes between both countries regarding water management, including over the issue of salinity of the Colorado River as it enters Mexico [85].

#### 4.3. Establishment of the TAAP

Both the US and Mexico have recognized that greater scientific understanding of their shared groundwater resources would be mutually beneficial, particularly within a region where groundwater is a primary component of the water balance and where populations are growing. The two countries signed the La Paz Agreement in 1983, which formally committed the US and Mexico to annual meetings between ministries and reviewing border environmental concerns. The agreement did not include any specific solutions or environmental protections but does provide a mechanism to do so in the future if

desired [86]. The US Congress authorized Public Law 109-448 in late 2006, whose formal name is the United States–Mexico Transboundary Aquifer Assessment Act (TAAA) [87]. Though the TAAA signaled US interest in participating in binational studies, Mexican concurrence was needed to proceed with a binational program and identification of aquifers of focus.

From 2007 to 2009, Mexico and the US began the engagement and negotiation process that resulted in approval by the IBWC of the “Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States–Mexico for the Transboundary Aquifer Assessment Program” (Joint Report [88]). The Joint Report guides the binational study of four transboundary aquifers: the San Pedro, Santa Cruz, Mesilla, and Hueco Bolson. The key word for the cooperation between the two countries is “assessment”—the Joint Report specifies that information that comes from cooperation is “solely for the purpose of expanding knowledge of the aquifers and should not be used by one country to require that the other country modify its water management and use” ([88], p. 3). Further, the Joint Report also states that activities should be beneficial to both countries and cannot limit what each country can do independently within its boundaries.

#### 4.4. Summary of Governance Principles Present

Some of the governance principles for management, planning, and assessment identified in the literature review are present in the TAAP case study. These elements have allowed for successful completion of scientific assessments but have not allowed for a transboundary management regime to manifest at this point.

*Stakeholder engagement* was one of the keys to the project’s success; a broad set of stakeholders and key actors was involved in early efforts that determined the scope of assessment. Stakeholder engagement efforts during the project have included establishing modes of communication through webpages, factsheets, and briefings. The project was most likely aided by the long history of binational stakeholder engagement in the region (see [89]).

There are no binding binational *management and planning* efforts regarding the TAAP aquifers. Aside from Minute 242, which does not involve any of the TAAP aquifers, there were no binding existing legal mechanisms dealing specifically with groundwater prior to the establishment of the TAAP. Elsewhere, the Municipal Water and Sanitation Board of the City of Juárez (Chihuahua, Mexico) and the El Paso Water Utilities Public Service Board (El Paso, TX, USA) signed a legally unenforceable and unofficial memorandum of understanding that calls for cooperation over and information exchange for the Hueco Bolson Aquifer in 1999 [90,91].

In addition to the absence of binding binational management and planning efforts, the two countries also have not engaged in binational *integrated water management*. There have been no binational efforts toward integrated water management elements such as managed aquifer recharge or collaborative modeling (though both countries have expressed interest in building binational models of the aquifers). Neither have there been any specific binational efforts toward *protecting groundwater resources* in terms of IBWC Minutes on water quality or quantity for the TAAP aquifers, though Minutes 261, 276, and 294 do designate impaired water quality resulting from border sanitation as an issue that should be addressed.

Though the IBWC had not previously had a specific focus on groundwater, it was undoubtedly a critical *functioning regional institution* for the function of the TAAP. The IBWC, along with CONAGUA, were key players for the development of the Joint Report. The IBWC’s expertise in managing treaty obligations (*previous water cooperation*) and Mexican policies regarding transboundary waters made the binational organization central in formalizing the cooperative framework [22].

*Funding* was provided by each country, but there were times when the timing of funding availability was asynchronous between the two countries. This resulted in differences between countries in the amount and type of work at a given time.

*Political will* was evident throughout the TAAP process. The approval of the TAAP had to go through multiple official channels, including the 2006 US TAAA and the IBWC. Stakeholder involvement was also significant in developing the assessment's parameters. Because the parties have limited their efforts to assessment, there has been no test of the political will associated with addressing the institutionally complex matter of joint management.

#### 4.5. Summary of Attributes for Information to Be Used in Decision-Making

*Saliency* of scientific information increases when the questions asked are relevant to actors involved. While binational priorities were developed jointly, some studies focusing on the TAAP aquifers were not binational as each country can conduct work within its own borders without needing to consult the other, in accordance with the Joint Report (e.g., [5]). Binational forums resulted in the development of strategic plans for the two Arizona–Sonora aquifers, outlining priorities and tasks, with annual tactical plans allow for more adaptive research to realities relating to funding, resources, personnel, and new progress [26].

The TAAP team attended and participated at conferences to communicate and exchange information with others in the scientific community. Team members have also disseminated journal articles, theses, and reports to enhance *credibility*. The Sonora–Arizona effort has yielded two reports: the *Binational Study of the Transboundary San Pedro Aquifer*, published in 2016, and the *Binational Study of the Transboundary Santa Cruz Aquifer*, which is undergoing peer review. Both studies address their attention to physical characteristics of the aquifers—the geology, climate, hydrology, landcover, and soils—and integrate these data across the entire geographic extent of the aquifer, evaluating it for the first time as a single physical system. Besides the work published by Pool and Dickinson [92] on the Sierra Vista Subwatershed and Sonoran portions of the Upper San Pedro Basin, binational maps were not common for the Transboundary San Pedro Aquifer. The same is true for the Transboundary Santa Cruz Aquifer, where only a few sources present harmonized binational cartography [93,94]. The San Pedro study produced 42 aquiferwide geographic information system (GIS) layers containing data about the aquifer, which served as the basis for the development of over 34 binational maps that describe multiple aspects of the study area [95]. Each of the two reports represents a one-of-a-kind type of assessment. The studies analyze and harmonize information from two different countries. Analyzing and harmonizing information required overcoming language barriers, institutional asymmetries, mapping and measurement preferences, and review processes.

Identifying each country's team members was one of the initial challenges of the TAAP. In Mexico, for example, some of the members were required by governmental policy to go through CILA for this task, as Mexico requires that all border water issues be handled through CILA. Universidad de Sonora and CONAGUA carried out the studies. US funding was divided among the federally authorized Water Resources Research Institutes in Texas, New Mexico, and Arizona, and the US Geological Survey Water Science centers in those three states, as required by the TAAA. Selection of team members who were bilingual also eased the process of communication.

#### 4.6. Interview Results

Officials interviewed from both countries agreed that the information generated from the reports could be used for recommendations and regulations (though were less certain about whether the information would help regulations), and an informal or formal binational groundwater organization. Interviewees said that the results are potentially useful for, e.g., confirming past conceptual understandings on the other side of the border, some adjudication decisions in Arizona, and providing information for other forms of decision-making. Figure 4 presents a summary of interviewees' scores for saliency, engaging stakeholders, bolstering trust and building relationships (interviews of scientists), and saliency, credibility, and legitimacy (interviews of government officials). The TAAP's

collaborative and iterative process of scientific assessment helped produce information that is more salient, credible and legitimate—regarding the transboundary aquifer—than could have been produced by either country alone (Table 1).

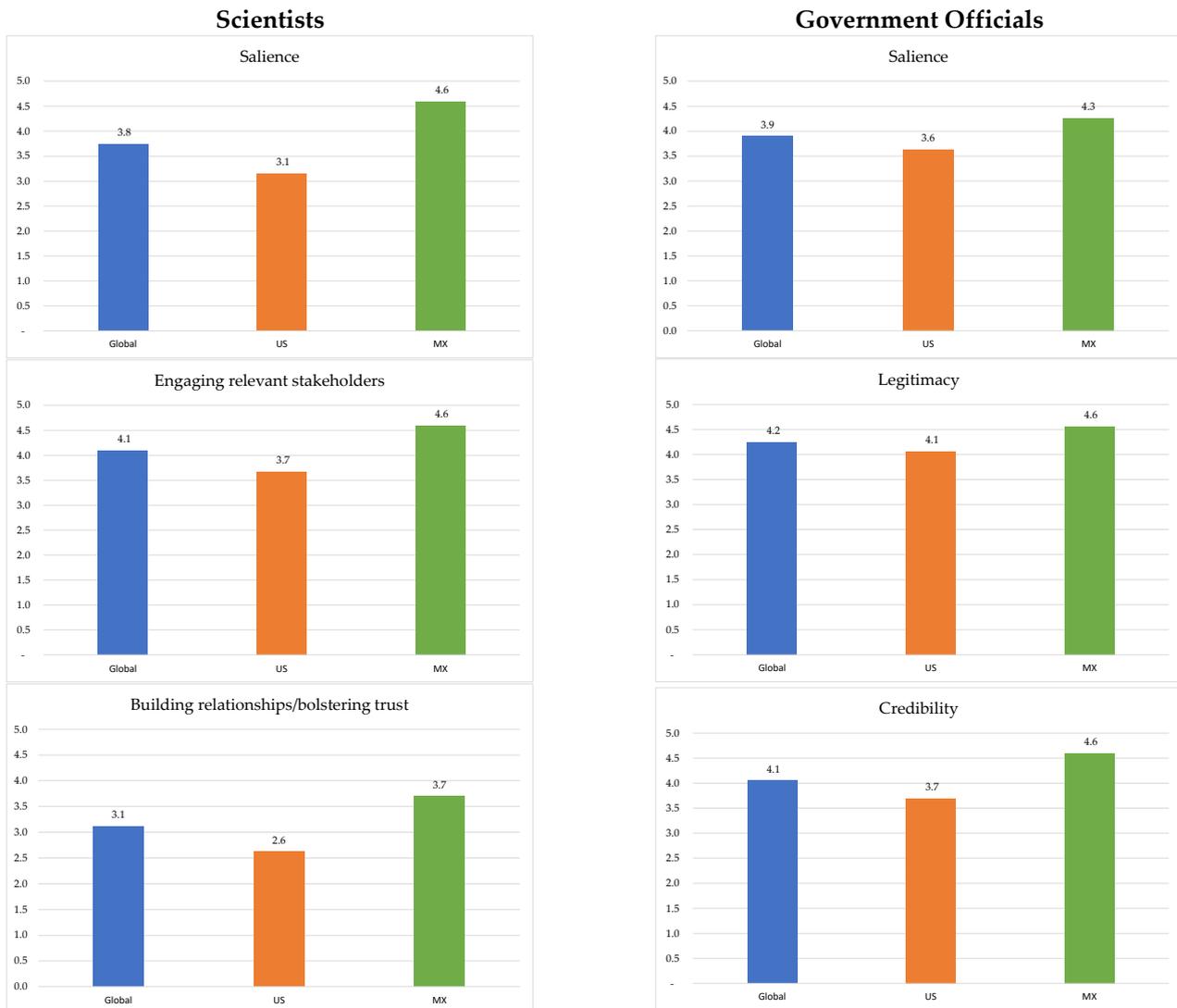


Figure 4. Summary of interview scores.

Table 1. Science production and relevant attributes of science outputs in the TAAP.

Features of Science Production	Relevant Attributes of Science Outputs
Binational development of research aims and focus areas through Binational Technical Group meetings	Legitimacy, salience, iteration
Investment of funding or in-kind investments from both countries	Legitimacy
Involvement of binational experts in knowledge production	Credibility, iteration
Stakeholder involvement in planning	Salience, legitimacy, iteration
Integration and harmonization of data from both nations	Salience, iteration
Bilingual reporting of results (Binational Studies of the San Pedro and Santa Cruz Aquifers)	Legitimacy

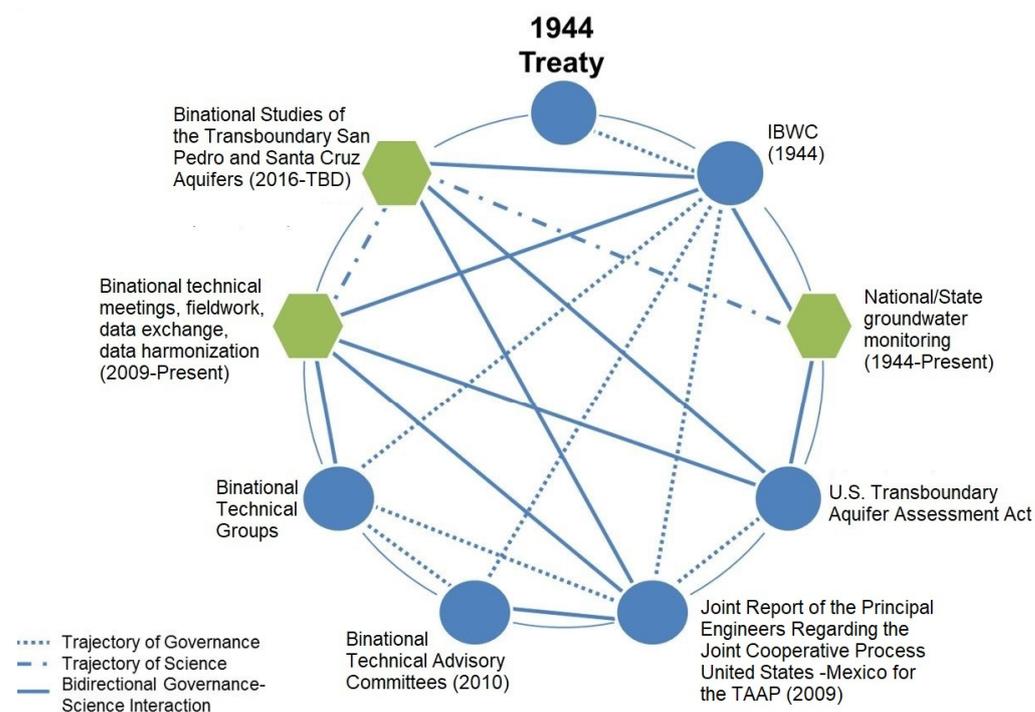
Regular and continuous communication and cooperation among the TAAP stakeholders also bolstered the *legitimacy* and acceptability of scientific information produced. The science produced by the Arizona–Sonora TAAP effort achieved legitimacy at the national level, gaining official approval by the governments of both the US and Mexico. Inclusion of social scientists in project design helped address social and institutional aspects of cross-border cooperation, which are critical to the production of legitimate knowledge.

No binational work contributing toward the assessment happened until the 2009 Joint Report. During this time, the Arizona–Sonora team engaged in team- and trust-building. Participation in field trips helped build trust and a shared history among team members. We define trust as an expectation or belief that one group can rely on another’s actions and word and/or that the group has good intentions toward others [96]. During the period of the study, the Binational Technical Group meetings established by the Joint Report also helped to build trust: “Through the collaborative work we have learned about the capacity and experience of the other researchers. It is not the same to know a person through what he or she has published as it is to work together with them,” one TAAP scientist said. The cooperative process was also aided by previous cooperative work conducted by Mexican and US geologists over the last 50 years. The *multiple iterations* of communication were essential for the process to continue and the work to be completed.

Both groups of Mexican officials and scientists interviewed for this article gave higher scores compared to their US counterparts in all six categories portrayed in Table 1. These higher scores could imply that Mexico perceives more benefits from the transboundary aquifer assessment process through sharing previous studies, data, and technical resources. The program also allows for arguably greater opportunities for Mexican researchers to expand their research networks compared to their US counterparts.

### 5. Bidirectionality and the Science–Policy Interface

Key elements of “good governance” and of collaborative scientific assessment processes both contributed to fruitful binational cooperation over assessment of these aquifers. We show the bidirectional interaction between groundwater governance and science production in Figure 5.



**Figure 5.** The path to bidirectionality/binationality in the TAAP. Governance elements are represented by blue circles; science elements are represented by green hexagons. Figure by authors.

The TAAP engaged in science production with joint research projects through the binational studies. Transboundary cooperation was established through trust and relationship building among actors. One TAAP scientist interviewed said, “The binational relations have been strengthened in many levels- [on the] local, formal, academic and research level, [we’ve engaged in] collaboration and [generated] trust, long term projects, medium term, joint collaboration.” Trust and relationship-building was aided by the already-established relationship between governments through the IBWC and other governmental avenues of cooperation. This was achieved through formal agreements in data and information sharing through the 1944 agreement and subsequent minutes. The establishment of a framework for a joint or collaborative binational study through the 2009 Joint Report helped to build a formal cooperation channel that was sheltered by the IBWC. Previous collaboration efforts lacked a coordinating body, Binational Technical Groups, and Binational Technical Advisory Committees. This led to ambiguities within studies and barriers associated to information distribution and availability.

In the context of US–Mexico transboundary groundwater, our view is that science can palpably contribute to US–Mexico groundwater governance (Hypothesis 1) in two key ways: (1) by informing management on each side of the border with a transboundary scientific understanding, and (2) by expanding binational cooperative networks—including communities of practice—on local, state, and national levels. These foundational cooperative elements allowed for a collaborative process of science production that goes beyond merely sharing information. From a “science-to-governance” perspective, collaborative scientific assessment of shared aquifers can help to inform water management decisions at the local (e.g., water rights adjudication in Arizona) and national (e.g., determining availability of groundwater in Mexico) levels, provides a shared knowledge-base and strengthened trust among participants. Multiple scientists said that the TAAP has helped scientists in learning to collaborate and promoted making contacts on the other side of the border. All scientists involved with the TAAP said that they have made new contacts thanks to the program: “Through this program we had the fortune to meet several researchers in the field and know what they do and be familiar with their work,” one TAAP scientist said. Another TAAP scientist said, “Because of TAAP, now I know who to go to [if I had a question about groundwater across the border].”

From a “governance-to-science” perspective (Hypothesis 2), the previous cooperation over water between Mexico and the US through the 1944 treaty and their subsequent minutes undoubtedly facilitated the establishment of the binational assessment process. Interviewed scientists said that the previous treaty and minutes helped to strengthen communication between countries.

The political will of stakeholders and policy makers played a significant role for the assessments. Funding provided by each country showed investment in the assessment’s outcome. The investment of time that it took for the parties to agree upon the 2009 Joint Report was arguably worthwhile, as it allowed them to create a document that struck a balance between independence—where both countries conduct and fund their own research activities on their side of the border—and coordination, including communication of information through sharing data publicly, e.g., through the publication of the assessments. Parties were able to harmonize information and overcome barriers, differences, and preferences through the Binational Technical Group and Binational Technical Advisory Committee meetings. The 2009 Joint Report guided how cross-border scientific efforts were carried out—e.g., via binational teams—which helped reduce the possibility that either nation would object to the knowledge produced. While one scientist pointed out that the 2009 Joint Report allowed for the assessments to happen, another scientist mentioned that it was an obstacle for them due to the level of formality associated with the protocol. The process for sharing data required multiple iterations. Both parties were initially cautious about sharing information. The data sharing process became more efficient as the studies progressed. Over time, scientists interviewed said that participation in multiple, face-to-face meetings built trust and relationships between team members. The meetings led to

collaborative science production by helping to resolve issues including jointly determining the delineation of the study area, data needs, and data integration and compatibility: “In both of those watersheds [San Pedro and Santa Cruz], there is a significant amount of data—making the results meaningful to stakeholders needs to be part of the package,” one US government official said. However, we should note that the results from scientists involved with the TAAP program may exhibit a more favorable view of the products resulting from the TAAP.

The IBWC was necessary as a coordinating body for the assessments. Its institutional capacity, (manifested through its authority in ensuring compliance with the 1944 treaty), its management of joint infrastructure and maintenance of hydrologic monitoring stations, its protocols for data exchange, its contribution of funding, and its role in transboundary communication, all contributed to helping the assessment process. With suitable adaptation for context, this effort could be replicable for other areas of scientific cooperation between Mexico and the US, and perhaps for other transborder-resource studies [97]. In the TAAP, steps taken on transboundary groundwater governance and production of scientific information built upon each other. This bidirectionality contributed to partially harmonize asymmetries in institutional frameworks between Mexico and the US, particularly because of the central role of the IBWC in its collection of binational data and coordination of the joint studies.

As an example of how governance elements and science production build upon each other bidirectionally, the TAAP process began with a joint decision regarding which aquifers would be assessed first. This consensus-based decision-making helped formulate project aims that are salient for stakeholders on both sides of the border. Datasets produced are comprehensive and harmonized across the border, in turn, allowing for better access to decision-makers and improved legitimacy of the information. Overall, the collaborative process enhanced legitimacy of the information produced through transparency and binational engagement. The resultant cross-border network of scientists and other stakeholders can be leveraged to help guide further efforts toward addressing shared goals. For instance, one TAAP scientist referenced how the TAAP has allowed for advancements in mapping geologic units that were beyond the scope of the original assessments.

There is no agreement to extend cooperation beyond scientific investigation and collaboration. However, if a more formal binational management regime were to come to pass (which appears unlikely according to interviewees), the availability of reliable scientific information would be an initial step [69,70,97–99]. From the outset, building trust and mutual respect have been important components of the assessment’s realization. Both countries would need to continue to build trust and navigate jurisdictional overlaps for a development of a binational management agreement, among other things.

It is possible that assessments such as the ones achieved by the TAAP will help to determine the severity of existing challenges and promote joint problem-framing and agenda-setting. Reaching a mutual understanding on aquifer and groundwater conditions is arguably a necessary (though not sufficient) condition for collaborative management. Such a strategy would help direct resources more efficiently to address the problems. That said, assessment can only go so far in leading to resolution of the groundwater management issues in the Santa Cruz and San Pedro aquifers. Rules, regulations, monitoring, enforcement of those rules and regulations, and perhaps most importantly, public acceptance, political will, and financial commitment are needed to resolve management issues. It appears likely that scientific assessments alone will need other factors to generate the political will necessary to create a binational management regime in this case or elsewhere.

There may be some potential for more localized cooperation between subnational jurisdictions within these aquifers. There has also already been informal, local cooperation in sharing water between the cities of Nogales, Arizona, and Nogales, Sonora, in times of serious drought in the Santa Cruz Aquifer [91] or during other specific problems such as fires [100].

## 6. Conclusions

This article argues, using the case study of the TAAP Sonora–Arizona assessments as an example, that transboundary groundwater governance and the production of scientific information evolve in reciprocal synchronicity—cooperation can enhance science production, and science can lead to advancements in policy. *Both* are needed for transboundary groundwater governance, as they are in nontransboundary situations. Certain elements of governance need to be present for scientific assessments to occur—particularly via collaborative efforts—and for the knowledge gathered through the efforts of the assessments to be potentially usable for future policy- and decision-making. In the case of the TAAP, the establishment of trust, the cooperative framework, and the history of cooperation between the two countries through formal agreements were particularly important to successful assessments. These components helped the binational team overcome challenges of integrating different standards and methods for reporting, peer review, language, measurement units, and technical and financial capacities, among others. While salience, credibility, legitimacy, and iterations of assessment and information-sharing can certainly aid further cooperation, it has yet to be seen whether the assessments will aid transboundary water governance between the two countries. Because of this, it should be noted that the case study is one example of bidirectionality, which may not be present in all cases. More evidence is needed from other cases to prove our argument.

More work lies ahead for policymakers to continue collaborative efforts after the completion of the assessments. A few questions about how momentum can be sustained, how the results of the assessments are being used, identifying the sources for financing, determining if political will exists to continue collaboration and progress to governance, and continuing the trust-building process, are yet to be answered. The politically charged issues surrounding water rights between the two countries also are yet to be solved. Despite the questions listed above, the TAAP case has several elements that enable groundwater collaboration. It is also consistent with some of the principles included in other groundwater management agreements around the world [99].

The TAAP case suggests that the relationship between data-cum-information-sharing and transboundary water governance is iterative and self-reinforcing. All discrete governance and information elements are part of a larger cooperative process. This process could help yield an eventual binational agreement (or agreements) such as those for the Genevois, Guaraní, Iullemeden, and Nubian aquifer systems. Since decision-making ultimately is a political process, we believe that, as elsewhere, science is a necessary condition for forging international groundwater agreements. Along with science, political will, stakeholder engagement, and adequate incentives to cooperate are critical factors for initiating and sustaining transboundary cooperation.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/w13172364/s1>, Table S1: Data on interviewees, Table S2: Interview questions for scientists, Table S3: Interview questions for government officials.

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