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Editorial

Advances in Transboundary Aquifer Assessment

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Advances in Transboundary Aquifer Assessment

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Editorial

Advances in Transboundary Aquifer Assessment

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Abstract: This Special Issue is intended to highlight both recent work to advance the physical understanding of transboundary aquifers and factors relevant in successful collaboration on transboundary groundwater resource use. The collected papers address: (1) the identification and prioritization of the needs and strategies for sustainable groundwater development and use, along with the complexities introduced by working across borders with differing governance frameworks, institutions, cultures, and sometimes languages; (2) the characterization of the physical framework of the aquifer, stressors on the aquifer system, and how those stressors influence the availability of groundwater in terms of its quantity and quality; and (3) the incorporation of stakeholder input and prioritization directly into the process of aquifer assessment and model building. The papers provide insights into the state of knowledge regarding the physical characterization of important transboundary aquifers, primarily along the U.S.–Mexico border and the opportunities for greater stakeholder involvement in resource evaluation and prioritization. They point the way towards a future focus that combines both of these aspects of transboundary aquifer assessment for informing groundwater management discussions by policymakers.

Keywords: transboundary aquifers; aquifer assessment; groundwater; stakeholder involvement; United States–Mexico border; United States–Canada border

1. Introduction

Groundwater serves the drinking water needs of about 50% of the global population and contributes to over 40% of the global production of irrigated crops. Over 40% of the world's water is transboundary in nature, crossing a binational border [1]. Management of the joint resource between countries involves the cooperation of multiple jurisdictions, sometimes with different languages and cultures. Management decisions about use of the groundwater resources require a physical understanding of the aquifer [2], including groundwater availability, stressors on the system, and the potential for sustainable groundwater use. Information about the physical system can support informed decisions by governments and managers regarding the shared resource. This Special Issue, "Advances in Transboundary Aquifer Assessment", is intended to highlight both recent work to advance the physical understanding of transboundary aquifers and factors relevant in successful collaboration on transboundary groundwater resource use.

Three themes emerged in the papers that comprise this Special Issue. The first theme "Transboundary governance and stakeholder engagement" (see Section 2.1) includes identifying and prioritizing needs and strategies for sustainable development and use, along with the complexities introduced by working across borders with differing governance frameworks, institutions, cultures, and sometimes languages. Papers in this section focus on the U.S.–Mexico border, with one paper addressing issues along the U.S.–Canada border. The papers focusing on "Aquifer characterization and assessment" (Section 2.2) involve the physical framework of the aquifer, stressors on the aquifer system, and how those stressors influence the availability and quality of groundwater. The papers in Section 2.3 "Integration of stakeholder input into model development" move beyond the reliance on

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physical data and expert opinion in aquifer assessment and model development to formally include stakeholder participation in the process of assessment and model building; these represent an effort to make models more responsive to current and developing issues and priorities in the aquifers being modeled.

2. Contributions

Much of the work described in the papers for this Special Issue was conducted under the umbrella of the Transboundary Aquifer Assessment Program (TAAP). Initiated through U.S. Congressional legislation in 2006 (U.S. Public Law 109–448, TAA-Act), the 2009 Joint Report of the Principal Engineers of the International Boundary and Water Commission (IBWC/CILA) [3], referred to as the TAAP Cooperative Framework, established the ability of the United States and Mexico to work together to study transboundary aquifers. The two countries agreed to focus on four aquifers: the San Pedro and Santa Cruz River aquifers along the border shared by the states of Arizona (United States) and Sonora (Mexico); and the Mesilla/Conejos-Médanos and Hueco Bolson aquifers along the border shared by New Mexico and Texas (United States) and Chihuahua (Mexico) (Figure 1). The choice of aquifers was based on the location of population centers, industry, and environmental concerns. Much of the work under TAAP has focused on these aquifers, and that focus is reflected in the topics covered in many of the papers in this collection.

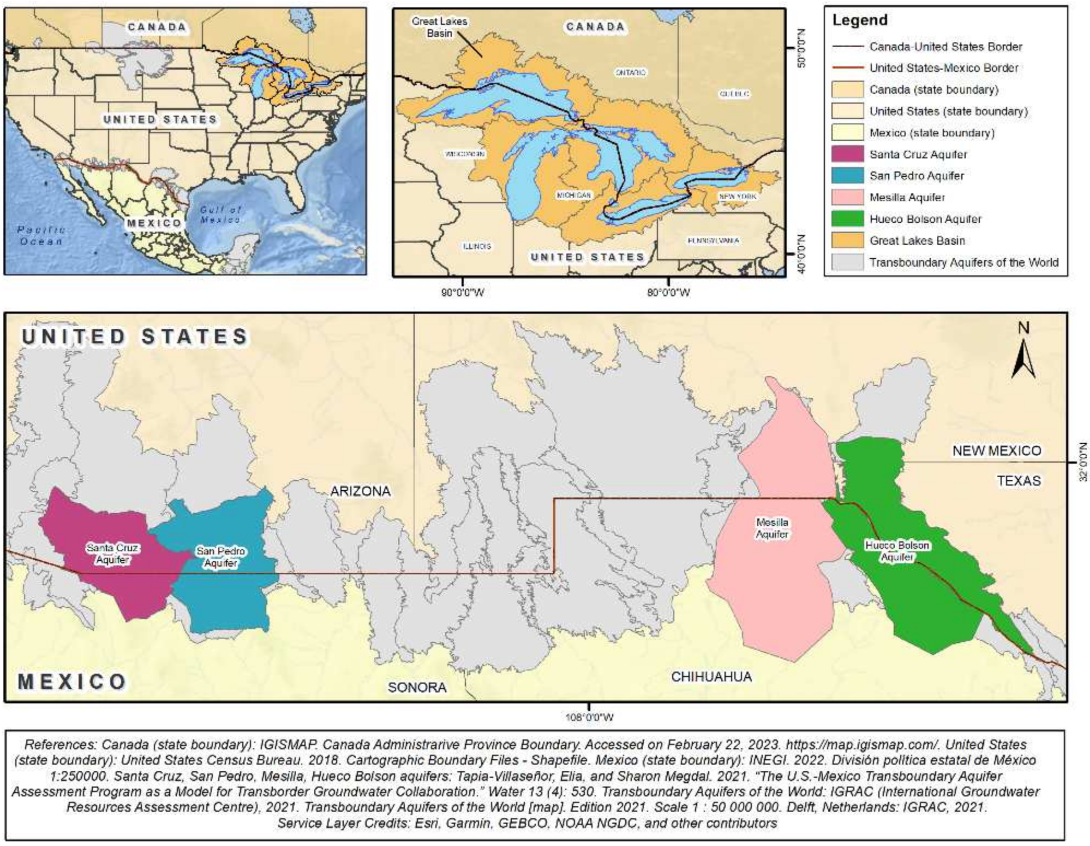

Figure 1. Location of aquifers discussed in the papers of this Special Issue, including the Transboundary Aquifer Assessment Program aquifers of focus and the Laurentian Great Lakes Basin (figure produced by Elia Tapia-Villaseñor; used with permission).

2.1. Transboundary Governance and Stakeholder Engagement

In some regions, water use and associated water governance have generally focused on more readily available surface-water resources, with laws and agreements governing groundwater storage and use lagging behind the ability to assess and use groundwater resources. This is the case for the Laurentian Great Lakes Basin along the U.S.–Canada border (Figure 1), the focus of Weekes and Krantzberg [4]. In their paper, "Twenty-first century science calls for twenty-first century groundwater use law: A retrospective analysis of transboundary governance weaknesses and future implications in the Laurentian Great Lakes Basin", they trace the development of water use and its regulation in the transboundary Laurentian Great Lakes Basin. Increasing population, with associated increases in water demand and land-use changes, has resulted in increased groundwater use. Coupled with climate change, increased groundwater use is driving a groundwater storage (GWS) decline. The Great Lakes are net groundwater receivers, and over-pumping aquifers can also reduce groundwater fluxes to surface-water systems. The GWS Governance framework, that is, policies and decision-making standards impacting GWS, are contained in binational-to-municipal-level statutes, voluntary agreements/regulations, common law, and treaties. Weeks and Krantzberg examine the history and development of GWS governance at the binational and at the province (state) levels. Although, in recent decades, groundwater specific policies have been developed, they note the prevalence of policies originally intended to safeguard surface water quantities interpreted to govern groundwater use and to maintain groundwater storage. Weekes and Krantzberg argue for the need to update groundwater policies and regulations to reflect current science and water use in the basin.

Focusing on processes that facilitate and support the integration of science and policymaking, Petersen-Perlman et al. [5], in "Science and binational cooperation: Bidirectionality in the Transboundary Aquifer Assessment Program in the Arizona-Sonora border region", observe that the use of scientific information in management and policymaking depends on salience, credibility, and legitimacy of scientific information; iterative information production; and sociocultural factors. Petersen-Perlman et al. look at six transboundary agreements globally, including TAAP, and note that the production of scientific information and governance, in the form of transboundary water cooperation over use of a shared resource, is iterative. Data production informs governance and policy, which in turn informs further data production. The process is bidirectional, in what the authors term "reciprocal synchronicity". A case-study analysis of TAAP finds that information sharing between the United States and Mexico was only possible after agreeing on and establishing the TAAP Cooperative Framework for data sharing and scientific collaboration between the countries. It has yet to be seen whether the assessments will aid transboundary water governance between the two countries.

Development of transboundary policies and governance between countries relies on collaborative processes that are articulated in some transboundary agreements. Tapia-Villaseñor and Megdal [6], in "The U.S.-Mexico Transboundary Aquifer Assessment Program as a model for transborder groundwater collaboration", note that TAAP was established as a program for the physical characterization of aquifers and is focused on binational information production. This knowledge–improvement phase is an element of the six global transboundary aquifer agreements examined in comparison to TAAP. Although not expressly stated, the binational nature of the TAAP Cooperative Framework, which establishes the ability of the United States and Mexico to perform transboundary assessments, implies and necessitates development of collaborative elements consistent with the principles of other transboundary groundwater management agreements around the world.

Tapia-Villaseñor and Megdal note that the principles of the TAAP Cooperative Framework include elements that promote trust between the United States and Mexico such as data sharing, development of binational aquifer assessment activities, the establishment of technical advisory committees, and the establishment of technical groups. In "Trust, risk, and power in transboundary aquifer assessment collaborations" [7], Brause examines the issue of trust in binational interactions in the Mesilla/Conejos-Médanos Basin, one of the TAAP designated priority transboundary aquifers, and the need to manage asymmetrical relationships of power and unequal levels of risk inherent in collaborating across the border. Brause observes that the TAAP Cooperative Framework does well to manage power inequalities at personal and interpersonal levels and in the context of organizing and managing collaborative exchange, but it cannot mitigate differences in structural power. Structural power differences are a greater issue at times of increased risk to a nation-state's ability to maintain sovereign control over its borderland water resources, such as an ongoing (2022) domestic water lawsuit in the United States that could affect water resources critical to Mexico (Texas v. New Mexico and Colorado, No. 141 Original, Eighth Circuit, United States Court of Appeals [https://www.ca8.uscourts.gov/texas-v-new-mexico-and-colorado-no-141-original]; accessed 15 October 2022).

2.2. Aquifer Characterization and Assessment

Papers in this Special Issue dealing with aquifer characterization examine the four TAAP aquifers of focus. In the San Pedro River aquifer, earlier work produced a hydrogeologic framework model with datasets such as geology, soils, and landcover, harmonized across the U.S.–Mexico border [8]. In "Hydrogeomorphologic mapping of the transboundary San Pedro Aquifer: A tool for groundwater characterization" [9], Minjarez Sosa et al. use datasets from the hydrogeologic framework model to develop a hydrogeomorphologic map of the San Pedro River Basin. Groundwater deficit in the aquifer is attributed to competing use from mining, military, domestic, and agricultural users. Mapping identifies potential areas of recharge in the highland and groundwater discharge in the lowland areas of the basin. This hydrogeomorphologic map can potentially serve as a tool for modeling and the development of strategies for sustainable water resource management.

Studies of the Santa Cruz River aquifer focus on the effects of climate variability and uncertainty on groundwater availability in the region. Shamir et al. [10], in "A Review of climate change impacts on the USA-Mexico Transboundary Santa Cruz River Basin" note current trends of year-round warming and a decline in precipitation and streamflow, especially in the winter months. A review of studies on climate uncertainty in the region in the mid-21st century identifies and describes a continuation of the current warming trend and a projected mid-21st century decline in precipitation events. These projected trends are important considerations in the development of strategies for sustainable water resources management of the Santa Cruz River aquifer. The findings of Shamir et al. are supported by the paper "Assessing groundwater withdrawal sustainability in the Mexican portion of the transboundary Santa Cruz River aquifer" [11]. Tapia-Villaseñor et al. develop a water-budget model for the Mexican portion of the Santa Cruz River aquifer to assess annual water withdrawal. Model results indicate a sharp decline in sustainable groundwater withdrawal for this part of the aquifer, from a maximum of 36.4 million cubic meters (MCM)/year in 1993 to less than 8 MCM/year in 2020, coincident with the drying period also identified in [10]. Based on their analysis, they point to a need to adjust water resource management criteria to respond to the large interannual climate variability in the region.

Because of their importance as regional water sources, there is a long history of research focused on the Mesilla/Conejos-Médanos and Hueco Bolson aquifers [12,13]. Four Special Issue papers focus on the physical assessment of these aquifers, expanding understanding of groundwater/surface-water interactions and of deep and interbasin groundwater circulation, and include a synthesis of Mesilla/Conejos-Médanos research and an updated hydrologic conceptual model. The Rio Grande/Río Bravo del Norte is the primary source of recharge to the Mesilla Basin/Conejos-Médanos aquifer system. Ikard et al., in "Gradient self-potential logging in the Rio Grande to identify gaining and losing reaches across the Mesilla Valley" [14], use gradient self-potential logging to survey an approximately 72 km reach of the Rio Grande from Leasburg Dam near the northern terminus of the Mesilla Valley downstream to Canutillo, Texas. By interpreting an estimate of the streaming-potential component of the electrostatic field in the river, they identify reaches where surface-water gains and losses were occurring and, therefore, areas of aquifer recharge and discharge along this portion of the Rio Grande.

Salinity contributions to the shallow Mesilla/Conejos-Médanos aquifer system and the Rio Grande come from several sources, including upwelling of geothermal groundwater. Pepin et al., in "Salinity contributions from geothermal waters to the Rio Grande and shallow aquifer system in the transboundary Mesilla (United States)/Conejos-Médanos (Mexico) Basin" [15], examine the potential contributions of deep saline groundwater from geothermal sources and demonstrate the use of heat as a groundwater tracer to identify salinity sources. Historical temperature data and groundwater flux estimates indicate that the region's known geothermal systems could account for 22% of Rio Grande salinity leaving the basin each year. Regional water level mapping indicates that upwelling brackish waters flow toward the Rio Grande and the southern part of the Mesilla portion of the basin.

In "Investigation of the origin of Hueco Bolson and Mesilla Basin Aquifers (US and Mexico) with isotopic data analysis" [16], Garcia-Vasquez et al. use the isotopic tracers δO^{18} and tritium to validate an interconnection between the Mesilla (U.S. portion) and Hueco Bolson aquifers. They combine new data from the Mexican portion of the Mesilla/Conejos-Médanos aquifer with results from the U.S. side of the aquifer [17]. Analyzing isotopic data from the Mesilla/Conejos-Médanos together with data from the U.S.–Mexico Hueco Bolson aquifer [18], Garcia-Vasquez et al. find evidence, as stated in [17] and [18], that the groundwater is old (recharged thousands of years ago). Their regional analysis supports groundwater exchange between the Mesilla and Hueco Bolson aquifers. These findings support an earlier geologic study [19] stating that the Mesilla/Conejos-Médanos and Hueco Bolson aquifers were originally part of a single aquifer system.

These more focused studies [14–16] contributed to a synthesis and refinement of the water budget and hydrogeologic framework model for the Mesilla/Conejos-Médanos aquifer [12]. In "Mesilla/Conejos-Médanos Basin: U.S.-Mexico transboundary water resources", Robertson et al. use an updated hydrogeologic framework, a binational water-level map, and previously reported aquifer property assumptions to estimate potentially recoverable fresh to slightly brackish groundwater in the Mesilla portion of the Basin at about 82,600 cubic hectometers (hm^3), largely in agreement with previous estimates. Storage for the Conejos-Médanos portion of the Basin is estimated at 69,100 hm^3. Based on evidence presented in this paper, the Rio Grande alluvium is the only unit currently receiving substantial amounts of recharge from the Rio Grande; the amount of groundwater in the Rio Grande alluvium represents a little less than 0.6% of the entire regional aquifer. The majority of groundwater stored in this basin is thousands to tens of thousands of years old. This water is very slowly being displaced at the boundaries by mountain-front recharge and near pumping centers, where vertical gradients are increased by large groundwater pumping withdrawals.

Work by Sanchez and Rodriguez [20], "Transboundary aquifers between Baja California, Sonora and Chihuahua, Mexico, and California, Arizona and New Mexico, United States: Identification and categorization" completes the western segment of a border-wide assessment of transboundary aquifers [21,22], using datasets and nomenclature harmonized across the U.S.–Mexico border. The combined border-wide assessment identified 72 transboundary hydrogeologic units, of which 50–55% were reported to have good to moderate aquifer potential and good to regular water quality. This combined work provides a high-level assessment to aid in identifying and prioritizing transboundary aquifers for further characterization and evaluation with respect to suitability for resource development.

2.3. Integration of Stakeholder Input into Model Development

Demonstrating a further development for these transboundary studies, we begin to see movement beyond reliance on physical data and expert opinion in aquifer assessment and model development to formally include stakeholder participation in the process of assessing, prioritizing issues of concern, and model building, with two papers focused on the Hueco Bolson and one on the Mesilla/Conejos-Médanos aquifer.

Hydraulic gradients and flow directions in the Hueco Bolson aquifer have changed because of high groundwater withdrawal rates in the two major cities, El Paso, United States and Ciudad Juarez, Mexico, raising questions about long-term aquifer sustainability [13]. Talchabhadel et al., in "Current status and future directions in modeling a transboundary aquifer: A case study of Hueco Bolson" [13], present an overview of the

Hueco Bolson aquifer modeling history and describe a coupled groundwater–watershed model currently (2021) under development. Given the complex set of stressors acting on this transboundary aquifer, they make the point that any sustainable and acceptable management solution will need all stakeholders' buy-in and knowledge co-production. They propose the development of a graphical quantitative modeling framework (e.g., system model and Bayesian belief network) to include expert opinions and enhance stakeholder participation in the model.

Focusing on stakeholder-driven assessment in the Hueco Bolson, Mayer et al., in "Investigating management of transboundary waters through cooperation: A serious games case study of the Hueco Bolson Aquifer in Chihuahua, Mexico and Texas, United States" [23], used a binational, multisector, serious-games workshop to explore collaborative solutions in extending the life of a shared aquifer. The workshop led to increased knowledge building on the part of the participants as well as an agreement on the importance of both binational action and informal binational collaboration in extending the life of the aquifer.

Finally, in a study that addresses the processes used to move between information creation and management decisions, Atkins et al., "Modeling as a Tool for Transboundary Aquifer Assessment Prioritization" [24], use a system dynamics model to quantitatively assess the dynamics of transboundary aquifer assessment information reporting and perception delays in the Mesilla/Conejos–Médanos Basin. The results show that the timing and content of reporting can change the dynamic behavior of natural, human, and technical components of transboundary aquifer systems. Atkins et al. demonstrate the potential for modeling to assist with prioritization efforts during the stakeholder data collection and exchange phases to ensure that transboundary aquifer assessments achieve their intended outcomes.

3. Conclusions

These papers provide insight into the state of knowledge regarding the physical characterization of important transboundary aquifers, primarily along the U.S.–Mexico border, and stakeholder inclusion in resource evaluation and prioritization, while pointing the way towards a future focus that combines both of these aspects of transboundary aquifer assessment. The papers in this Special Issue build on prior TAAP work and other studies. Physical assessment is informed by and can inform questions about binational groundwater management, which is the purview of policy makers. Binational assessment enables the parties to develop a common scientific framework and understanding about groundwater and aquifer conditions, while fostering binational relationships. Methodologies are proposed for incorporating expert opinions and stakeholder participation directly in model and scenario development. These efforts suggest that characterization of the complexities of the physical systems and consideration of binational stakeholders and governance can inform development of sustainable management strategies.

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