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Prioritizing Transboundary Aquifers in the Arizona–Sonora Region: A Multicriteria Approach for Groundwater Assessment

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Abstract: Groundwater is vital to the well-being of over 20 million people in the nearly 2000-mile-long, arid U.S.–Mexico border region, supporting agricultural, industrial, domestic, and environmental needs. However, persistent droughts over the past two decades, coupled with increasing water demand and population growth, have significantly strained water resources, threatening the region's water security. These challenges highlight the importance of comprehensive transboundary aquifer assessments, such as those conducted through the Transboundary Aquifer Assessment Program (TAAP), a collaborative effort between the U.S. and Mexico to evaluate shared aquifers. The TAAP focuses on four aquifers: the Santa Cruz and the San Pedro in Arizona and Sonora and the Mesilla and the Hueco Bolson in Texas, New Mexico, and Chihuahua. With the need for additional aquifer studies in this arid region, it is important to determine and prioritize which aquifers would benefit most from transboundary assessment. This study aims to prioritize aquifers in the Arizona–Sonora region based on multiple criteria. The results from this study reveal regional disparities in the need for transboundary aquifer studies, with some aquifers highlighted due to their groundwater use for economic activities, while others stand out for their population density and the transboundary nature of the hydrogeologic units. By leveraging publicly available data, this research established a priority ranking for these aquifers to support decision-making processes in identifying and addressing the most critical aquifers for binational assessment, while providing a framework that can be replicated across other shared aquifers between the U.S. and Mexico and elsewhere.

Keywords: transboundary aquifers; assessment; prioritization; United States; Mexico

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1. Introduction

In the U.S.–Mexico border region, groundwater serves as the sole or primary water source for many communities [1]. Over the past two decades, persistent drought conditions have exacerbated concerns about water security in the region, threatening both human and economic development [2,3]. In the Arizona–Sonora border area, these challenges are further aggravated by climate uncertainties, with projections indicating a 5- 10% reduction in annual precipitation during both summer and winter seasons [4]. Such changes increase the risk of surface-water and groundwater deficits, carrying profound implications for human well-being and environmental health.

The growing awareness of groundwater conditions has made aquifer assessments increasingly important for researchers, decision-makers, and water users. Aquifer assessment activities are central to the Transboundary Aquifer Assessment Program (TAAP), a collaborative effort between the United States and Mexico to evaluate shared aquifers.

Established in 2006 under the Transboundary Aquifer Assessment Act (U.S. Public Law 109-448, also known as TAA-Act), the program authorized the United States Geological Survey (USGS) and the Water Resources Research Institutes (WRRIs) of Arizona, New Mexico, and Texas to partner with Mexican counterparts in developing transboundary aquifer assessments [5]. The TAA-Act specifically authorized studies of the Santa Cruz and San Pedro aquifers, shared by Arizona in the United States and Sonora in Mexico, as well as the Mesilla and Hueco Bolson aquifers, shared by Texas and New Mexico in the United States and Chihuahua in Mexico. These aquifers were selected based on their proximity to highly populated areas, increasing groundwater demands, and water quality concerns [6]. The binational TAAP was formally established in 2009 with the signing of the Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States–Mexico for the Transboundary Aquifer Assessment Program (TAAP Cooperative Framework) by the U.S. and Mexican sections of the International Boundary and Water Commission (IBWC) [7].

The TAAP Cooperative Framework allows either country to propose an aquifer for study, provided the proposal is of mutual interest [7]. However, P.L. 109-448 restricted the designation of additional priority aquifers along the Arizona–Sonora border, aiming to exclude the Colorado River portion of Arizona's border region from the TAAP [8]. In 2023, H.R. 5874, introduced by Representative Juan Ciscomani of Arizona's District 6, proposed amendments to extend the TAA-Act's authorization and permit the designation of additional priority aquifers along the Arizona–Sonora border, excluding the Yuma groundwater basin [8]. Both the TAAP Cooperative Framework and H.R. 5874 highlight the program's potential for fostering binational collaboration on transboundary aquifer assessments.

The TAAP has advanced groundwater characterizations in the Arizona–Sonora border region, including studies on the Transboundary San Pedro River Aquifer [9], water balance modeling for the Transboundary Santa Cruz River Aquifer [10–12], and assessments of U.S.–Mexico groundwater governance [13–15], among others. These efforts have deepened the understanding of the region's physical characteristics, particularly regarding the impacts of groundwater recharge and demand on water availability. While progress continues for the San Pedro and Santa Cruz aquifers, the shared characteristics of climate, aridity, and groundwater use across neighboring aquifers highlight the need to expand research beyond these current focal areas.

The prioritization of aquifers and basins is increasingly common among land and water managers, who use various strategies for different objectives. For example, California prioritizes groundwater basins into four categories—high, medium, low, and very low priority—based on criteria such as population, irrigated acreage, groundwater reliance, and ecological impacts [16]. In Illinois, groundwater protection is addressed through designated Groundwater Protection Planning Regions, in which regional committees advocate for protective measures and engage stakeholders [17]. Similarly, Arizona employs a prioritization tool for springs, focusing on conservation value, threats, and ecological significance [18]. Multicriteria strategies also enhance prioritization efforts; for instance, Vishwakarma et al. (2021) [19] applied an analytical hierarchy process (AHP) and GIS to identify managed aquifer recharge sites in semi-arid regions, while Rodriguez-Merino et al. (2020) [20] used GIS-based multicriteria decision analysis to assess vulnerability in protected areas. Within the U.S.–Mexico border context, Atkins et al., 2021 explored the application of system dynamics modeling as a tool for prioritizing transboundary aquifer assessments, focusing on the Mesilla Basin/Conejos-Médanos Aquifer [21].

Globally, the United Nations Environment Programme's 2016 report [22] on transboundary river basins highlights indicators such as water quantity, quality, governance, and socioeconomics for assessing risk and prioritization. Many of these indicators—such as water stress, pollution, and economic reliance on water—are relevant to the TAAP's characterization and prioritization efforts.

This study aims to prioritize aquifers in the Arizona–Sonora region using multiple criteria, leveraging publicly available data critical to regional water security and aligning with global prioritization efforts. The purpose of this study is to inform and guide decision-makers in identifying and addressing the aquifers most in need of assessment, ensuring that resources are allocated effectively to areas in which they can have the greatest impact. The findings are intended to provide a foundation for prioritizing shared aquifers along the Arizona–Sonora border, with methodologies adaptable to other transboundary aquifers in the U.S.–Mexico border region.

2. Materials and Methods

2.1. Study Area

This study utilizes a multicriteria analysis (MCA) approach to prioritize aquifers that require assessment, particularly within the transboundary region of Arizona–Sonora. According to the United Nations International Law Commission's Draft Articles on the Law of Transboundary Aquifers, a transboundary aquifer is defined as an aquifer or aquifer system that spans two or more state boundaries. An aquifer is described as a "permeable water-bearing geological formation underlain by a less permeable layer, with water contained in the saturated zone of the formation". Sanchez et al. (2016) [23] identified and characterized transboundary aquifers along the U.S.–Mexico border, classifying them based on their level of transboundary confidence. They identified at least 36 transboundary aquifers along the border, based on geological connectivity, known hydrological flows, and administrative limits. Of these, 10 were located within the Arizona–Sonora region (Figure 1). The International Groundwater Resources Assessment Centre (IGRAC) updated the Transboundary Aquifers of the World Map in 2021 [24], aligning with Sanchez et al.'s findings; however, discrepancies regarding the exact number of transboundary aquifers persist. For instance, Mexico's National Water Commission (CONAGUA) recognizes only five transboundary aquifers in the Arizona–Sonora border region: the Valle de San Luis Río Colorado–Yuma, Sonoyta–Puerto Peñasco–San Simon Wash System, Nogales, Santa Cruz, and San Pedro aquifers [25]. This study examined the following Arizona–Sonora border aquifers:

1. Valle de San Luis Río Colorado–Yuma Aquifer: Spanning 6403.59 km^2 (2472.44 mi^2), this aquifer supports a population of 383,860 across Yuma, Somerton, San Luis Río Colorado, and Wellton [26,27]. Yuma plays a critical role in the U.S. agricultural sector, producing a significant portion of the nation's lettuce, while San Luis Río Colorado is known for its wheat and cotton production [28,29]. Although information about this aquifer is provided for context, it is excluded from the multiple-criteria evaluation due to TAA-Act restrictions on its assessment.
2. Los Vidrios–Western Mexican Drainage Aquifer: Covering 7189.21 km^2 (2775.77 mi^2), this sparsely populated aquifer partially encompasses the municipalities of Puerto Peñasco and Ajo, with a total population of only 53 inhabitants [26,27] (INEGI, 2020). The aquifer's primary community, Lukeville, Arizona, has 35 residents and serves as a transit point for travelers heading to Puerto Peñasco, Sonora.
3. Sonoyta–Puerto Peñasco–San Simon Wash System: Encompassing 14,731.45 km^2 (5687.84 mi^2), this aquifer supports 79,339 people. Key communities include Sonoyta, Puerto Peñasco, and Quitovac in Mexico, as well as the Tohono O'odham Nation in the U.S. indigenous settlements, including the Tohono O'odham Nation and Pápagos.
4. Arroyo Seco/Tucson AMA Aquifer: As delineated by Sanchez et al. (2016) and IGRAC (2021), this aquifer spans 12,501.60 km^2 (4826.90 mi^2) and supports nearly

948,171 people, including the city of Tucson and Florence. However, Tucson's reliance on the Colorado River, the limited evidence of transboundary connectivity for this aquifer, and the fact that Florence is not part of the Tucson AMA, lead to its omission from the multicriteria evaluation.

5. Río Altar Aquifer: This 2794.24 km^2 (1078.86 mi^2) aquifer supports 11,188 residents in Altar, Sáric, and Tubutama in Mexico. This aquifer does not cross the international border and there is limited evidence of transboundary connectivity, as expressed by Sanchez, 2016 [23].
6. Río Alisos Aquifer: Covering 890.13 km^2 (343.72 mi^2), this aquifer is connected to the Transboundary Santa Cruz Aquifer system through inter-basin water transfers to supply the city of Nogales, Sonora, which relies on water from three different aquifers within Mexican territory [10]. The Río Alisos Aquifer does not cross the international border.
7. Santa Cruz Aquifer: This TAAP aquifer of focus spans 3890.85 km^2 (1502.26 mi^2) and supports 306,989 people, including the Ambos Nogales region [26,27]. Cross-border trade and agricultural activities necessitate substantial water resources for cultivation and industrial processes [30].
8. San Pedro Aquifer: Spanning 4468.57 km^2 (1725.13 mi^2), this TAAP aquifer of focus supports 116,019 residents, including those in Sierra Vista and Cananea [26,27]. Major water users in this region include mining operations, agriculture, and military activities [31,32].
9. Douglas–Agua Prieta Aquifer: Covering 3780.28 km^2 (1459.57 mi^2), this aquifer supports 115,749 people, including the towns of Douglas and Agua Prieta [26,27]. Cross-border commerce, manufacturing, and agriculture rely heavily on the aquifer's water resources [29,33].
10. Arroyo San Bernardino–San Bernardino Valley Aquifer: The aquifer boundary partially covers the municipalities of Agua Prieta in Mexico and Elfrida and Douglas in the United States. The aquifer comprises a total population of 108, based on the population of the towns and cities within the aquifer [26,27].

2.2. Multicriteria Analysis

Multicriteria analysis (MCA) techniques are widely recognized for their effectiveness in facilitating water management decision-making, as highlighted by Alamanos et al. (2018) [34] and Rodriguez-Merino (2020) [20]. MCA methods provide a structured approach to help managers and decision-makers assign weights to criteria based on their relative importance, enabling the evaluation of alternatives and supporting the identification of priorities for further action [20,35]. This methodology is particularly well suited for this research as it integrates multiple dimensions—such as population density, groundwater availability, and transboundary connectivity—into a coherent decision-making framework. This integration is essential for prioritizing aquifers in which diverse hydrological, social, and environmental factors interact. The inclusion of these factors would not be feasible using single-criterion assessments, hydrological modeling, or cost–benefit analysis, which are also common methods for decision-making related to water resources.

The MCA process involves evaluating a set of predefined criteria and alternatives, allowing for the selection of optimal decisions through systematic pairwise comparisons [36]. While several methodologies can be employed for MCA, one of the most commonly used approaches is to assign weights to criteria based on expert opinions [35]. This process typically uses a pairwise comparison matrix, in which each criterion is compared against others on a relative scale, producing a priority ranking. This technique, widely known as the

Analytic Hierarchy Process (AHP), was introduced by Saaty (1987) [36] and is instrumental in identifying the relative importance of criteria within a decision-making framework.

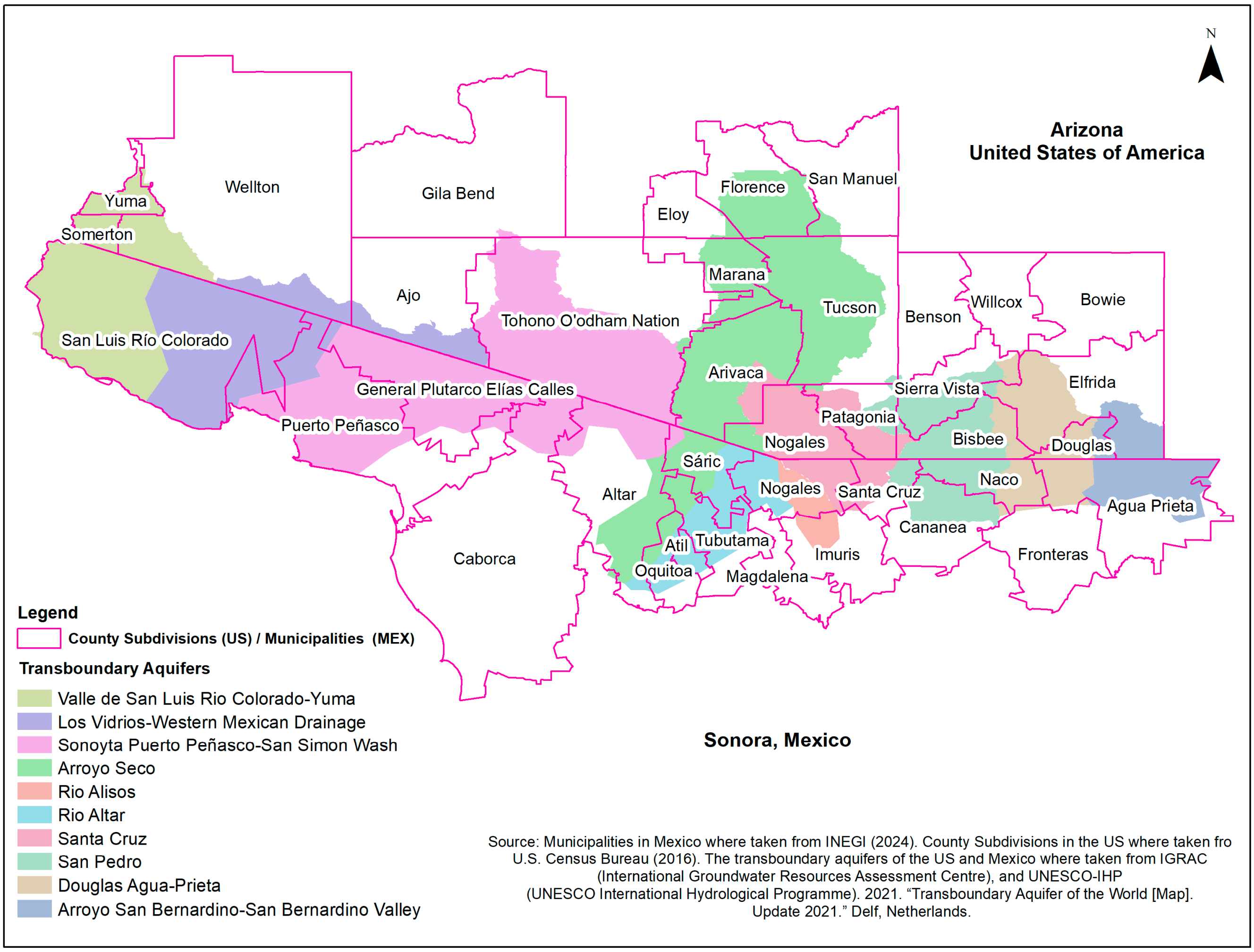

Figure 1. Arizona–Sonora border aquifers.

The initial step in the MCA process involves identifying the problem and organizing it into a hierarchical framework comprising three main levels: (i) the objective, (ii) the criteria, and (iii) the alternatives. The objective defines the overarching goal of the decision-making process; the criteria represent the factors used to evaluate alternatives; and the alternatives are the possible options under consideration. In this study, the primary objective is to prioritize aquifers in the Arizona–Sonora region for investigation.

Building on established methodologies, this study draws from the evaluation framework for environmental risk assessment developed by the United Nations Environment Programme [22] and the groundwater basin prioritization methodology implemented by the California Department of Water Resources [16]. Key criteria were selected to provide a comprehensive understanding of the current state of the aquifers. These criteria were chosen to ensure compatibility with available data for both the U.S. and Mexican portions of the Arizona–Sonora aquifers and to enable applicability to other transboundary aquifers along the border.

Although water-quality information is highly relevant for such analyses, its exclusion was necessary due to limited availability for some of the Mexican aquifer portions. The selected criteria instead focus on quantifiable and available metrics, such as population density, transboundary confidence, groundwater availability, and aridity, among others, ensuring a practical and robust evaluation of aquifer conditions.

2.2.1. Data Sources and Criterion Selection

For this study, criteria were selected based on the availability of information, its reliability, and the potential applicability of these datasets to other aquifer regions. This section describes each criterion, its relevance, and the corresponding sources of information:

- Population Density: This criterion evaluates the concentration of people living within the aquifer's limit. It reflects human demand for water resources, as a higher population density is often associated with a greater groundwater demand and a higher potential for water quality and availability issues. This criterion helps prioritize aquifers by considering how densely populated areas may influence changes in water resources, making aquifers with higher population densities more critical for research. The population was determined using GIS tools, U.S. Census Bureau (2020) [26], and INEGI (2020) [27] data. The population within each city and town that comprised each aquifer was aggregated to identify the total population within the aquifer.
- Transboundary Confidence: The confidence level in the transboundary nature of each aquifer is categorized into three tiers—reasonable, some, and limited—based on the framework established by Sanchez et al. (2016) [23] and as reported in subsequent studies [37,38]. This classification relies on an evaluation of geological and administrative criteria to determine the degree of transboundary connectivity. In this AHP analysis, aquifers with higher transboundary confidence levels are assigned greater priority, emphasizing their importance in managing and understanding cross-border water resources.
- Groundwater Availability: This criterion evaluates the balance between groundwater recharge and extraction to assess groundwater availability [39–47]. In Mexico, the National Water Commission (CONAGUA) is mandated under the National Water Law and its regulations to publish the annual average availability of groundwater for each aquifer, as outlined in the Official Mexican Standard NOM-011-CONAGUA-2015 [48]. This standard provides the specifications and method for determining groundwater availability through a water balance approach. The calculation involves estimating the total recharge (R) to the aquifer, subtracting the natural discharge (DNC), and further deducting the volume of groundwater extraction (VEAS). Groundwater availability (DMA) is expressed as $DMA = R - DNC - VEAS$, where a positive value indicates a surplus and a negative value reflects overextraction or resource stress. While CONAGUA's groundwater availability studies are specific to Mexican aquifers, they provide a valuable framework for assessing sustainability trends in a binational context by providing insights into the balance between recharge and extraction. The results for this criterion are expressed in Millions of Cubic Meters (MCM) per year.
- Transboundary Groundwater Flow: This criterion assesses the horizontal flow of groundwater across the international boundary, which is an important indicator of the interconnectedness and shared dependency on transboundary aquifer systems. Transboundary groundwater flow data for this study were derived from the water availability reports published by CONAGUA for the aquifers under consideration [39–47]. According to the Official Mexican Standard NOM-011-CONAGUA-2015 [48], the groundwater discharge of an aquifer is calculated by applying Darcy's law to specific outflow sections, which are defined based on the configuration of groundwater levels. This calculation incorporates variations in groundwater levels over the time period analyzed, providing an estimate of the volume of water flowing horizontally through

the aquifer. The results for this criterion are expressed in Millions of Cubic Meters (MCM) per year.

- Groundwater Wells: This criterion is based on the number of registered groundwater wells in both the United States and Mexico. The data for the United States were obtained from the Arizona Department of Water Resources GIS Data portal (https://gisdata2016-11-18t150447874z-azwater.opendata.arcgis.com/ (accessed on 1 September 2024)) [49], while the data for Mexico were sourced from the Public Registry of Water Rights maintained by CONAGUA (https://app.conagua.gob.mx/consultarepda.aspx (accessed on 1 September 2024)) [50]. The number of wells is used as a proxy for groundwater extractions, with the assumption that a higher number of wells corresponds to greater extraction pressure on the aquifer system, thereby increasing its priority for assessment. This assumption arises from the lack of consistent and homogenous well information across the United States and Mexico. In the United States, relevant well data include information on well depth, water level, casing depth, type and diameter, and pump rate (rated pumping capacity). In contrast, Mexico's registry provides information on well use and the groundwater concessions granted by the federal government. A concession specifies the allowable volume of water that can be extracted from a particular well or aquifer. These concessions typically have durations ranging from five to thirty years, with the possibility of renewal upon expiration. To gain a more accurate understanding of actual groundwater usage, flow meters or water accounting systems are recommended to monitor and record the total volume of water extracted over time. However, such systems are not available for all wells within the border region, presenting a challenge for the comprehensive assessment of groundwater use.
- Aridity: In this AHP analysis, an aridity index (AI) was developed by the authors to evaluate the historical climatological stress of the basin. The aridity index (AI) measures the degree of climatic dryness based on the annual ratio of precipitation to potential evapotranspiration and the changes in barren land cover within the basin. A lower AI indicates a more arid region, and an increase in barren land cover signals greater desertification. The AI was calculated using the TerraClimate dataset [51].
- Irrigated Lands: This criterion assesses the extent of land irrigated using groundwater resources. Larger irrigated areas typically indicate higher water demand, placing significant pressure on the aquifer. The data were obtained from national census surveys published by the Food and Agriculture Organization (FAO) and the World Bank. The dataset development is described in Siebert et al., 2005, 2007, and 2013 [52–54] and can be downloaded at https://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/latest-version/ (24 June 2024). The results are presented in hectares (Has) of irrigated lands.

2.2.2. Assigning Weights to Criteria

Assigning weight to each criterion is a key step in the development of MCA, as it determines the relative influence of each criterion on the decision-making process [20]. In this study, the focus is on aquifer prioritization, and the analytical hierarchy process (AHP), developed by Saaty (1987) [36], is employed as a structured framework to evaluate the relative importance of criteria through pairwise comparisons. In this method, each criterion is compared with the others using a fundamental scale of importance (e.g., equal, moderately more important, strongly more important). These comparisons are organized into a matrix to capture relative preferences. The matrices are then normalized to derive priority vectors, which are numerical weights ranging from 0 to 1, reflecting the relative importance of each criterion. For example, since this study focuses on transboundary aquifers, criteria such as transboundary confidence and transboundary groundwater flows were assigned higher weights, reflecting their greater importance compared to other criteria. Finally, the priority level for each aquifer was calculated using the following formula:

$$\text{Priority Level} = (\text{Weight Criterion 1} \times \text{Weight Alternative 1} \times \text{Result Alternative 1}) + (\text{Weight Criterion 2} \times \text{Weight Alternative 2} \times \text{Result Alternative 2}) + \ldots + (\text{Criterion j} \times \text{Weight Alternative j} \times \text{Result Alternative j}).$$

3. Results

The criteria considered in this MCA included population density, transboundary confidence, groundwater availability, transboundary groundwater flow, number of wells, aridity index, and irrigated lands. Table 1 provides a summary of the evaluated criteria for eight aquifers within the Arizona–Sonora border region; Table 2 presents the weight of each criterion; and Figure 2 illustrates the process for determining the level of priority.

Table 1. Transboundary aquifers and evaluated criteria.

Aquifer Name	Aquifer Area (km^2)	Population	Population Density (Person/km^2)	Transboundary Confidence	Groundwater Availability (MCM */Year)	Transboundary Groundwater Flow (MCM/year)	No. of Ground-water Wells	Aridity Index (% Change)	Irrigated Lands (Hectares)
Los Vidrios–Western Mexican Drainage	7189.21	53	0.01	Some	0.00	4	MX: 1 U.S.: 33 Total: 34	−24.9	374
Sonoyta–Puerto Peñasco–San Simon Wash	14,731	79,339	5.4	Reasonable	−83.72	9	MX: 525 U.S.: 27 Total: 552	−19.2	5495
Río Altar	2794	11,188	4.0	Limited	0.00	7.3	MX: 558 U.S.: 0 Total: 558	−12.5	9146
Río Alisos	890	3264	3.7	Limited	0.00	0	MX:173 U.S.: 0 Total: 173	−12.7	2196
Santa Cruz	3891	306,989	78.9	Reasonable	0.00	2	MX: 297 U.S.: 3855 Total: 4152	−14.3	2965
San Pedro	4469	115,749	25.9	Reasonable	−6.71	10.8	MX: 177 U.S.: 5883 Total: 6060	−13.6	1054
Douglas–Agua Prieta	3780	116,019	30.7	Reasonable	−0.05	2.6	MX: 127 U.S.: 4009 Total: 4136	−12.5	5035
Arroyo San Bernardino	2658.08	108	0.04	Some	0.00	8.4	MX: 25 U.S.: 249 Total: 274	−12.1	364

Note: * MCM: Millions of cubic meters.

Eight transboundary aquifers in the Arizona–Sonora region were analyzed using a multicriteria approach that assigned a priority level based on a weighted set of criteria. The resulting priority rankings were as follows: (1) Sonoyta–Puerto Peñasco–San Simon Wash System, (2) Santa Cruz, (3) San Pedro, (4) Douglas–Agua Prieta, (5) Los Vidrios–Western Mexican Drainage, (6) Río Altar, (7) Arroyo San Bernardino–San Bernardino Aquifer, and (8) Río Alisos Aquifer. Table 3 provides a summary of the priority levels for each aquifer, with values closer to 1 indicating very high priority and values closer to 0 representing very low priority.

Table 2. Weight of each criterion for transboundary aquifer prioritization.

Criteria	Weight of Criteria	Alternative	Weight of Alternative	Unit of Alternative
Population density	0.125	■ 0–20 ■ 20–40 ■ 40–60 ■ 60–80	■ 0.096 ■ 0.161 ■ 0.277 ■ 0.466	Persons per square kilometer
Transboundary confidence	0.226	■ Limited ■ Some ■ Reasonable	■ 0.164 ■ 0.297 ■ 0.539	NA
Groundwater availability	0.113	■ −25–0 ■ −50–−25 ■ −75–−50 ■ −100–−75	■ 0.096 ■ 0.161 ■ 0.277 ■ 0.466	Millions of cubic meters (MCM/year)
Transboundary groundwater flow	0.173	■ 0–40 ■ 40–80 ■ 80–120 ■ 120–160	■ 0.096 ■ 0.161 ■ 0.277 ■ 0.466	Millions of cubic meters (MCM/year)
Groundwater wells	0.113	■ 0–100 ■ 100–1000 ■ 1000–10,000 ■ 10,000–22,000	■ 0.096 ■ 0.161 ■ 0.277 ■ 0.466	Number of wells
Aridity	0.125	■ −12–−16 ■ −16–−20 ■ −20–−24 ■ −24–−26	■ 0.096 ■ 0.161 ■ 0.277 ■ 0.466	Relative change in aridity index (%)
Irrigated lands	0.125	■ 0–3000 ■ 3000–6000 ■ 6000–9000 ■ 9000–13,000	■ 0.096 ■ 0.161 ■ 0.277 ■ 0.466	Hectares

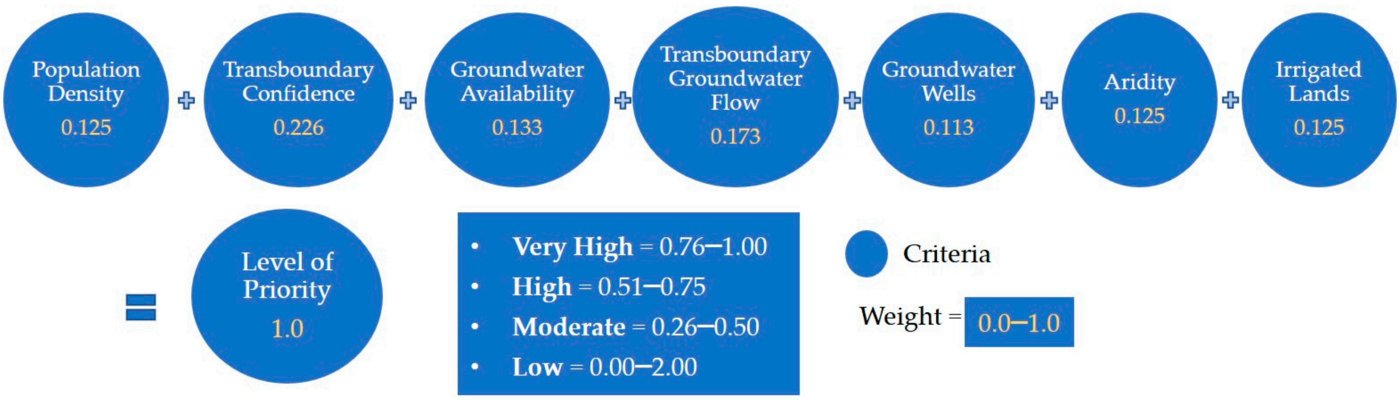

Figure 2. Transboundary aquifer prioritization process.

As expected, the Santa Cruz and San Pedro aquifers, currently prioritized under TAAP, ranked high for transboundary assessment. Notably, the highest priority was assigned to the Sonoyta–Puerto Peñasco–San Simon Wash System, characterized by reasonable transboundary confidence, a significant groundwater deficit of −83.72 MCM/year, 525 registered wells, 5495 hectares of irrigated lands, and an aridity index of −19.2%. These factors, combined with the remaining analyzed criteria, contributed to its top-ranking priority. In comparison, the groundwater availability for the Santa Cruz and San Pedro aquifers, at 0.0 and −6.17 MCM/year, respectively, was less pronounced than the deficit observed in the Sonoyta–Puerto Peñasco–San Simon Wash System, which partially explains its higher prioritization score. Following the Santa Cruz and San Pedro aquifers, the Douglas–Agua Prieta Aquifer ranked next, with a minor groundwater deficit of −0.05 MCM/year, 4136 registered wells, an aridity index of −12.5%, and 5035 hectares of irrigated lands. The remaining aquifers, including Los Vidrios–Western Mexican Drainage, Río Altar, Arroyo San Bernardino–San Bernardino Valley, and Río Alisos, were assigned moderate-to-low priority, reflecting a lesser immediate need for studies based on the evaluated criteria.

Table 3. AHP scores and level of priority.

Aquifer Name	Population Density	Transboundary Confidence	Groundwater Availability	Transboundary Groundwater Flow	No. of Ground-water Wells	Aridity Index	Irrigated Lands	AHP Score	Level of Priority
Sonoyta–Puerto Peñasco–San Simon Wash System	0.096	0.539	0.466	0.161	0.161	0.161	0.161	0.564	1
Santa Cruz Aquifer	0.477	0.539	0.096	0.096	0.277	0.096	0.096	0.546	2
San Pedro Aquifer	0.161	0.539	0.096	0.277	0.277	0.096	0.096	0.529	3
Douglas–Agua Prieta Aquifer	0.161	0.539	0.096	0.096	0.277	0.096	0.161	0.481	4
Los Vidrios–Western Mexican Drainage	0.096	0.297	0.096	0.096	0.096	0.466	0.096	0.388	5
Río Altar	0.096	0.164	0.096	0.161	0.161	0.096	0.466	0.364	6
Arroyo San Bernardino–San Bernardino Valley Aquifer	0.096	0.297	0.096	0.161	0.161	0.096	0.096	0.331	7
Río Alisos Aquifer	0.096	0.164	0.096	0.096	0.161	0.096	0.096	0.245	8

4. Discussion

Multicriteria analysis is widely applied in decision-making processes, with evaluation criteria tailored to the objectives of the analysis. For instance, the Illinois Environmental Protection Agency prioritizes aquifers based on water quality, while California's methodology integrates water quality alongside aquifer conditions and groundwater availability. In this study, although water quality was recognized as a potentially valuable criterion for identifying aquifers in need of assessment, the lack of comparable data across the U.S.–Mexico border precluded its inclusion.

By contrast, the United Nations Environment Programme (UNEP) transboundary basin assessment incorporates broader criteria related to water quantity, water quality, ecosystems, governance, and socioeconomics. While governance factors such as the presence or absence of legal frameworks, hydro-political tensions, and enabling environments are important in broader transboundary contexts, they are less applicable in the context of this study. Given that this assessment focuses on aquifers shared by only two nations and lacks accepted or accessible measures for some of these variables, incorporating such criteria would have introduced challenges in quantification and interpretation. Another significant limitation was the absence of consistent well data from both sides of the border, which restricted the inclusion of groundwater level trends as a criterion. Groundwater level data could provide valuable insights into the long-term dynamics of aquifer stress; however, inconsistent monitoring and data availability remain a challenge. This finding emphasizes the need for binational efforts to establish standardized monitoring systems for groundwater levels and water quality across the border region.

Despite these limitations, the prioritization effort yielded valuable results. It identified aquifers experiencing significant groundwater stress and highlighted those that should be prioritized for assessment in the following order: (1) Sonoyta–Puerto Peñasco–San Simon Wash System, (2) Santa Cruz, (3) San Pedro, (4) Douglas–Agua Prieta, (5) Los Vidrios–Western Mexican Drainage, (6) Río Altar, (7) Arroyo San Bernardino–San Bernardino

Aquifer, and (8) Río Alisos Aquifer. Both the San Pedro and Santa Cruz aquifers received high-priority rankings for assessment, consistent with their status as the two TAAP aquifers of focus in Arizona and Sonora, validating their selection as priority aquifers fifteen years after their designation. Notably, the Sonoyta–Puerto Peñasco–San Simon Wash System received a slightly higher score than these two aquifers, primarily due to its extreme groundwater deficit, harsh aridity conditions, and significant number of groundwater wells.

The Douglas–Agua Prieta Aquifer ranked fourth and has been identified as a potential site of interest by members of the United States and Mexican TAAP teams. The Río Altar and Río Alisos aquifers, located solely within Mexican territory but included in IGRAC's Transboundary Aquifers of the World map, showed limited evidence of interconnection with hydrogeologic units across the border and, therefore, received moderate- and low-priority rankings, respectively. These aquifers were included in this MCA because they are listed in the IGRAC 2021 Transboundary Aquifers of the World Map. On the other hand, the Los Vidrios–Western Mexican Drainage and the Arroyo San Bernardino–San Bernardino Valley Aquifer, which are sparsely populated, also received moderate and low rankings.

This methodology provides a robust framework for future transboundary aquifer assessments, offering flexibility for adaptation based on regional data availability and assessment priorities. It is recommended that these studies be complemented with stakeholder input, a possible next step in the aquifer-prioritization process. Additionally, the data gathered and evaluated during this process represent valuable information for land and water managers. For instance, determining the total population living within an aquifer's boundaries presents a challenge, as a single aquifer can span multiple municipalities and counties. This study addressed this gap by using GIS tools and census data from both countries to identify towns and cities located within aquifer boundaries. A similar analysis was conducted to assess the number of wells within each aquifer. These datasets, along with information on groundwater availability, transboundary flows, aridity, and irrigated lands, were selected to balance the use of readily available data. This approach ensures that the methodology remains accessible and replicable while capturing key insights. Finally, the selected datasets provide a foundation for informed actions that can enhance the understanding and responsible use of shared water resources.

5. Conclusions

The prioritization of transboundary aquifers through a multicriteria analysis approach has proven to be an effective method for identifying aquifers in need of assessment. Results for the Arizona-Sonora region border aquifers validated the prioritization of the San Pedro and Santa Cruz aquifers, consistent with their status as Transboundary Aquifer Assessment Program aquifers of focus. Additionally, the identification of the Sonoyta–Puerto Peñasco–San Simon Wash System as the highest-priority aquifer highlights the need to address extreme groundwater deficits and aridity conditions in this region. Challenges associated with inconsistent monitoring and data availability across the U.S.–Mexico border hindered the inclusion of certain relevant criteria. However, the information that was uniformly gathered from both sides of the border provides sufficient context to identify stressors related to groundwater use and availability. These limitations highlight the importance of coordinated binational efforts to standardize data collection and integration, which would strengthen the reliability of future assessments. This framework can also be applied to other transboundary aquifers along the U.S.–Mexico border and globally, aiding in the identification of aquifers most in need of assessment based on regional priorities.

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