

## Article

# Hydrogeomorphologic Mapping of the Transboundary San Pedro Aquifer: A Tool for Groundwater Characterization

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**Abstract:** Hydrogeomorphology is an emerging discipline that studies the relationship between landforms and hydrology, focusing on groundwater and surface water interactions. This study presents the methodology for the elaboration of a hydro-geomorphological map oriented to illustrate the relationships between the aquifer components and geomorphological characteristics in the United States-Mexico Transboundary San Pedro Aquifer (TSPA). This information contributes to a further understanding of the TSPA, facilitates the location of groundwater recharge and discharge zones, is useful for the development of sustainable groundwater management strategies, and could be useful in developing conceptual and numerical groundwater models for the region.

**Keywords:** hydrogeomorphology; transboundary aquifer; recharge; discharge; United States; Mexico



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## 1. Introduction

Granular and fractured aquifers represent an important source of fresh water in arid and semi-arid regions that are highly dependent on groundwater resources. Factors such as climate, topography, geomorphology, and lithology influence groundwater-flow interactions [1–4]. However, groundwater availability ultimately relies on the rainfall rate of the site, and the location and characteristics of the aquifer's recharge and discharge zones [2,3,5]. A better understanding of these areas contributes to the development of groundwater-management plans and strategies that promote water-resources sustainability, which is essential in transboundary settings where water resources are shared by two or more countries. Hydrogeomorphologic studies have proven to be useful for investigating the associations between landforms and hydrological processes that affect surface-water and groundwater flow, identifying the potential impacts of changes in land-use practices, and locating possible groundwater recharge and discharge areas [1,5–11].

A term first introduced in 1972, hydrogeomorphology broadly described the study of landforms produced by different hydrologic processes [10]. Over the years, hydrogeomorphology evolved into “an interdisciplinary science that focuses on the interaction and linkage of hydrologic processes with landforms or earth materials and the interaction of geomorphic processes with surface and subsurface water in temporal and spatial dimensions” [11]. Frequently, geomorphologic and hydrogeomorphologic studies have focused on flood assessment and surface-water controls, landslide assessment, and in atmosphere-hydrosphere-lithosphere interactions [12–15]. On the other hand, hydrogeomorphologic studies have also been associated with the analysis of groundwater resources (e.g., [1,5–7]). For instance, hydrogeomorphologic mapping allowed the identification and classification of hydro-objects in Southern Italy and the modeling of catchment contribution areas [16]. Additionally, scholars in this area of study have defined the connection between landforms and hydrology and expressed the need for a holistic approach that considers the

relationships among landscape engineering, agriculture, natural areas, and water-resources management [17].

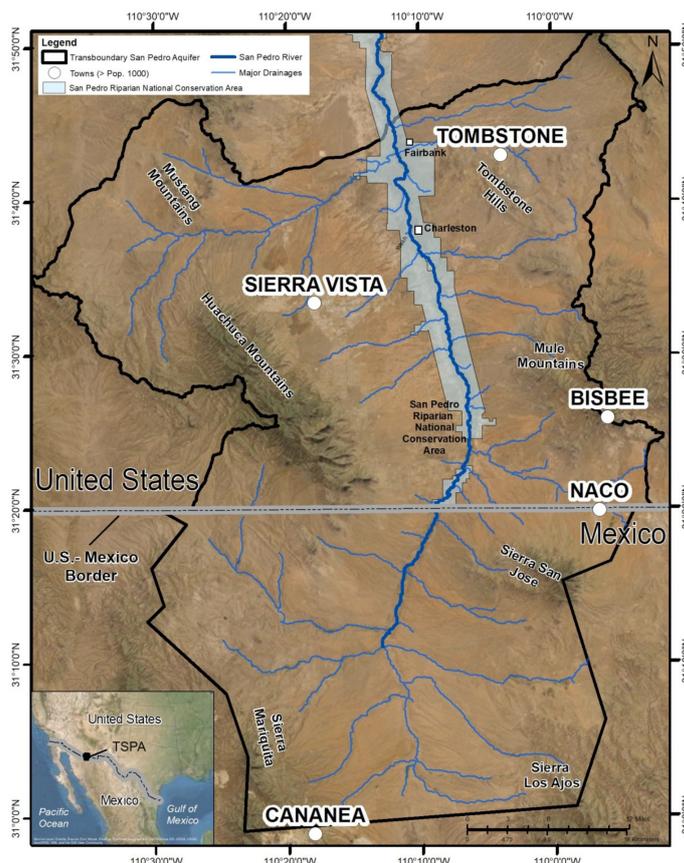
The importance of using criteria including landform, elevation, lithology, and hydrology for the assessment of groundwater resources has been described by Chaminé et al. (2015) [18]. In the arid Río Asunción Basin of Sonora, México, the correlation between the basin's groundwater-storage capacity and its lithologic units, ability to resist weathering and erosion, and presence of faults was described by Gutiérrez Anguamea (2013) [6]. The mapping methodology presented by [6] was later used for the development of a hydrogeomorphologic map for the state of Sonora, Mexico [7], an approach published in collaboration with the Mexican National Water Commission (CONAGUA) that serves as a guide for water-resources management in the region.

Located in Northwestern Mexico, the state of Sonora is bordered to the north by the state of Arizona in the United States. The United States and Mexico share history, culture, people, and water. A recent transboundary-characterization study indicates that based on geological correlations, there are 72 hydrogeologic units, or aquifers, that cross the U.S.-Mexico border [19]. One of these aquifers is the Transboundary San Pedro Aquifer (TSPA), located in the Arizona-Sonora border region. The TSPA is a Transboundary Aquifer Assessment Program (TAAP) aquifer of focus, which is a joint effort between the United States and Mexico to evaluate shared aquifers [20–23]. A number of studies and technical activities have been carried out through the TAAP in Arizona and Sonora over the last decade (i.e., [22–25]). For example, in 2016 the International Boundary and Water Commission published the Binational Study of the Transboundary San Pedro Aquifer [24]. This study, jointly developed by TAAP partners from the two countries, binationally described the physical geography, geology, hydrology, hydrogeology, and hydro-geochemistry of the TSPA. In this study, we aim to contribute to the TAAP knowledge base by using hydrogeomorphologic mapping as a tool for groundwater characterization, a novel approach that could guide land and water-management decisions in both the United States and Mexico.

## 2. Study Area

Located in the eastern portion of the Arizona-Sonora border, the TSPA is drained by the San Pedro River (Figure 1). The San Pedro River has its headwaters east of Cananea, Sonora, and flows northward to the United States until its confluence with the Gila River. The San Pedro River sustains hundreds of species—for example, it is an important bird habitat—and the basin contains one of the major unfragmented landscapes in the Southwest [26]. Several authors who have studied the aquifer basin have reported concerns regarding the impact of groundwater pumping on the San Pedro River, an ongoing issue that has captured the attention of scientists and stakeholders within the region [24,26–28].

The TSPA has an approximate area of 5000 km<sup>2</sup> and a population of around 97,235 (Table 1). The climate in this border region is arid to semi-arid with bimodal patterns of precipitation characterized by intense summer rains associated with the North American Monsoon and winter precipitation associated with the presence of Pacific cold fronts [24,27]. The mean annual precipitation in the Mexican portion of the TSPA has been reported to be 553 mm [28]. On the other hand, 330 mm were reported in Tombstone, and 960 mm on the Huachuca mountains in Arizona [24]. Mean annual temperature was reported to range between 12 °C and 18 °C [24]. The TSPA is located in the Basin and Range Province, bordering the Sonoran and Chihuahuan Deserts [24,27].



**Figure 1.** The Transboundary San Pedro Aquifer (TSPA). Source: Authors’ development based on Callegary et al. (2016) [24].

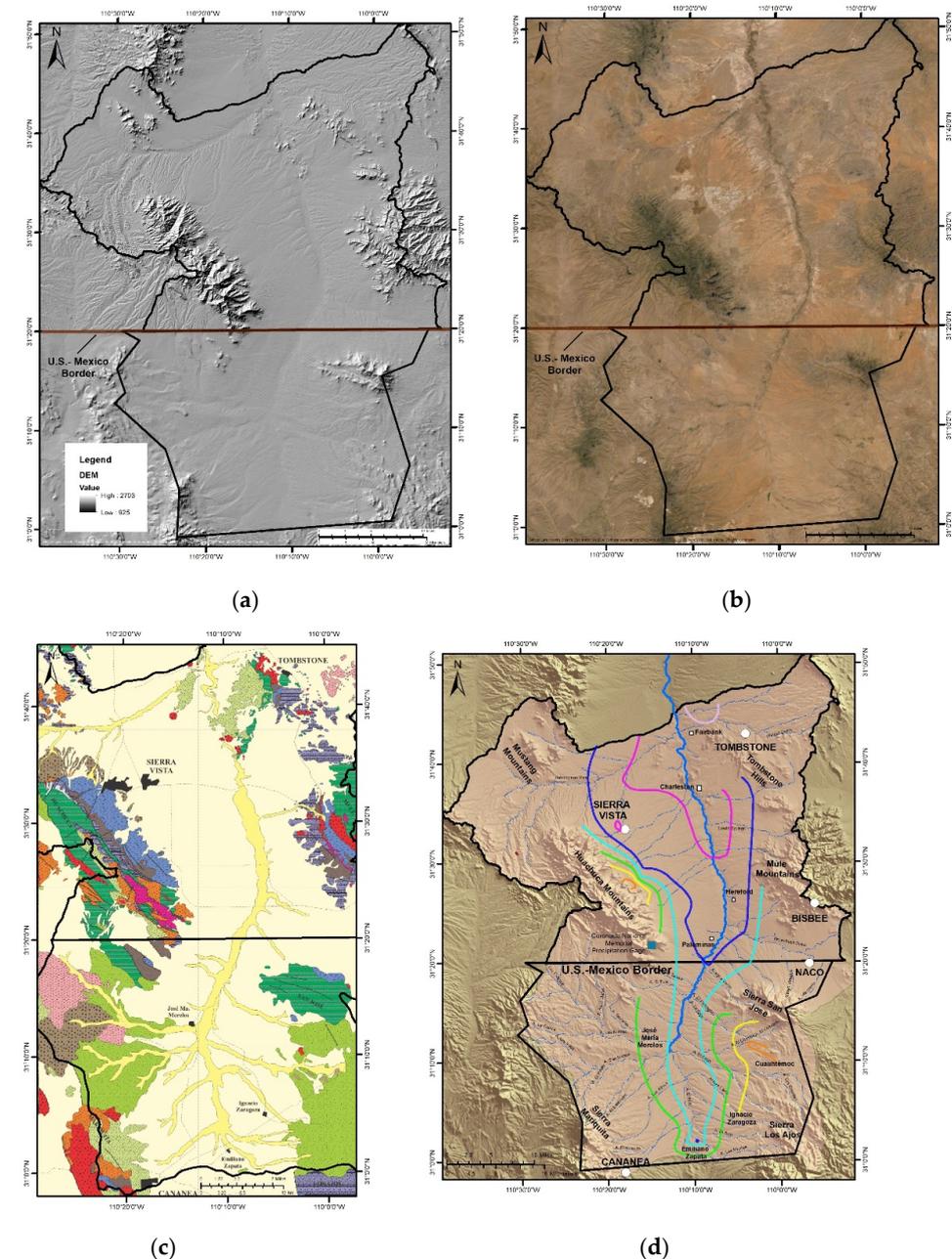
**Table 1.** Population centers located in the TSPA. Source: INEGI, 2010, INEGI, 2020, U.S. Census Bureau 2020 [29–31].

Town	Population
Sierra Vista	45,308
Tombstone	1209
Naco	6064
Bisbee	5203
Cananea	39,451
Total	97,235

The major economic activities within the region include tourism and military operations in the United States, and livestock, agriculture, and mining in Mexico [24]. According to data from the Mexican Public Registry of Water Rights [32], 82 wells are registered in the Mexican portion of the TSPA under the following activities: 41 for livestock activities, two for industrial uses, 14 for agricultural uses, and 25 for public, urban, residential, and miscellaneous uses. Annual groundwater extractions from these wells equals 30.67 million cubic meters per year (MCM/year) [32], and in 2015, the aquifer registered an annual groundwater deficit of  $-7.49$  MCM [28]. In 2014, groundwater demand in the U.S. portion of the TSPA, the Sierra Vista Sub-watershed, was reported to be 38.38 MCM/year (31,119 acre-feet per year) [33]. This region also reported a groundwater deficit of 5.21 MCM (4229 acre-feet per year) during the same year [33].

### 3. Materials and Methods

In this study, we analyzed the satellite imagery available through the ArcGIS Online Server [34] and combined the geologic and hydrogeologic information [24], and the topographic features (Digital Terrain Model SRTM1N30W109V3, [35]) to identify composition, topographic arrangement, and the presence or the absence of structures (see Figure 2). A visual inspection of satellite imagery allows for the differentiation of rock units based on the identification of textures and tones, i.e., smoothness, roughness, and compaction [36–38].



**Figure 2.** GIS layers used for the development of the hydrogeomorphologic map of the TSPA. (a) Digital Elevation Data [35]; (b) Satellite Image [34]; (c) Geology and Structures [24]; (d) Hydrography and Groundwater Levels [24].

### 3.1. Topographic Characterization (Landform Identification)

A topographic characterization was carried out using the Digital Terrain Model information available for the study site [35]. Elements within the study area were classified into four major types of terrain (described below): mountains, hills, piedmonts, and plains [39].

**Mountains:** Landforms with a relative height greater than 200 m, associated with endogenous folding processes, magmatism, vulcanism, and the dissection of endogenous formation structures [40]. Relative heights were considered from the base to the top of each formation analyzed in this study.

**Hills:** Landforms with a relative height less than 200 m. This group originates from the leveling of mountains (endogenous) or the dissection of a sloping plain (erosive exogenous). However, hills may be associated with low-elevation endogenous landforms or the product of quaternary tectonics [41].

**Piedmonts:** Mountainous margins or transitional zones distinguished by a change of slope and considerably lower height, ranging from 0 to 200 m depending on the behavior of the terrain. Piedmonts are composed of detrital material and present fluvial drainage [6,40].

**Plains:** Land surfaces with minimal slope and altitude difference. Correspond to the cumulative exogenous terrain of alluvial, wind, and coastal deposits [6,40]. The following factors were considered in the identification of a plain: land use (agricultural and urban), change in slope, and drainage pattern.

### 3.2. Geologic Characterization

A diverse tectonic evolution has shaped a complex geology in the TSPA with intrusive, metamorphic, volcanic-sedimentary, sedimentary, and volcanic rocks [24,30]. A Precambrian basement covered by sedimentary platform sequences—mainly carbonates—is exposed along southeastern Arizona/northeastern Sonora [24,30]. The oldest Mesozoic rocks within this region are Jurassic volcanic and sedimentary sequences covered by Cretaceous-Tertiary rocks, which are widely distributed throughout the TSPA [24,30]. The lithological units considered in this study, based on Callegary et al. (2016) [24], are shown in Table 2.

**Table 2.** Lithological units in the TSPA. Source: Authors' development based on Callegary et al. (2016) [24].

Legend	Lithostratigraphic Units	Description
	Precambrian Igneous-Metamorphic Complex	Igneous and metamorphic rocks
	Early Paleozoic Sedimentary Unit	Localized outcrops of detrital-carbonate rocks within the Mexican portion of the TSPA
	Late Paleozoic Sedimentary Unit	Limestone and sandstone exposed in most topographic highs in the TSPA
	Jurassic Felsic Volcano-Sedimentary	Intercalation of volcanic rocks, sandstones, agglomerates, basalt flows, sills, and intermediate composition
	Jurassic Intrusive Complex	Intrusive hypabyssal bodies mainly exposed on the U.S. side of the TSPA
	Late Jurassic–Early Cretaceous Sedimentary Unit	Conglomerate, sandstone, shale, and limestone from the Bisbee Group
	Late Cretaceous Sedimentary Unit (KsVs, Ks)	Sedimentary sequences

Table 2. Cont.

Legend	Lithostratigraphic Units	Description
	Cretaceous–Paleocene Volcano-Sedimentary Unit	Rhyolitic clastic and volcanic rocks
	Tertiary–Cretaceous Intrusive Complex	Intrusive felsic rocks
	Tertiary Felsic Volcanic Unit	Rhyolitic rocks from the west-central portion of the TSPA
	Tertiary Volcano-Sedimentary Unit	Continental rocks, mainly conglomerates with intercalations of sandstone and tuff
	Plio–Quaternary Sedimentary Unit	Coarse sediments (gravels and sands) distributed within the center of the TSPA
	Alluvium	Gravel, sands, silts, and clay.

### 3.3. Hydrological and Hydrogeological Information

The proposed hydrogeomorphologic map includes hydrological and hydrogeological data for a better visualization of the impact groundwater extractions have on the aquifer’s distinct units. Information for this study includes a spatial layer with the hydrology, the locations of wells, and the groundwater levels for the year 2011. In addition, we identified the permeability, hydraulic conductivity of the rock units based on Gutiérrez Anguamea (2013) [6] and Freeze and Cherry (1979) [3] (Figure 3).

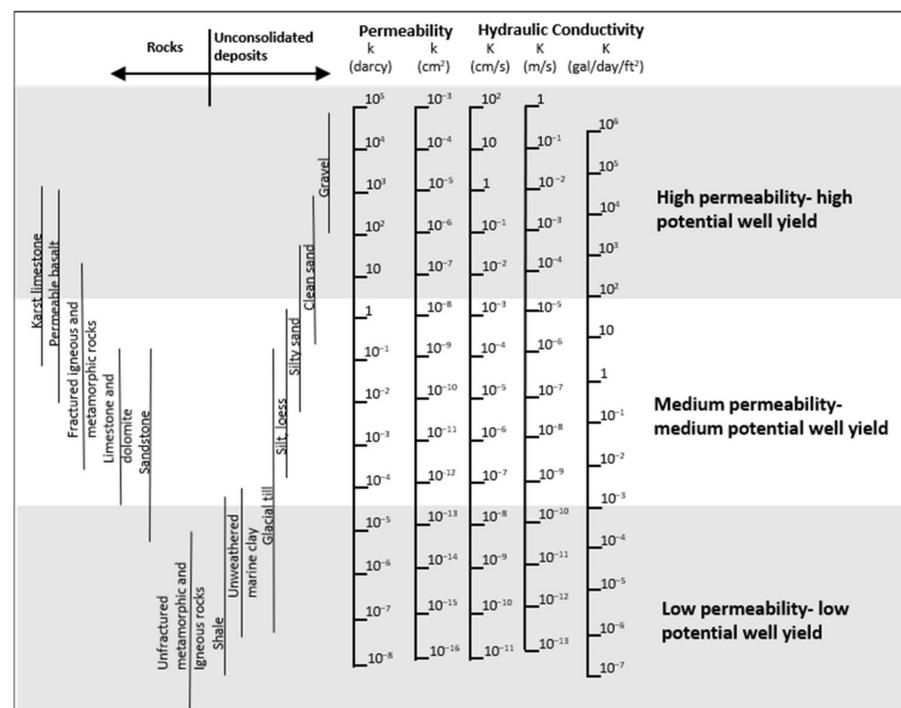
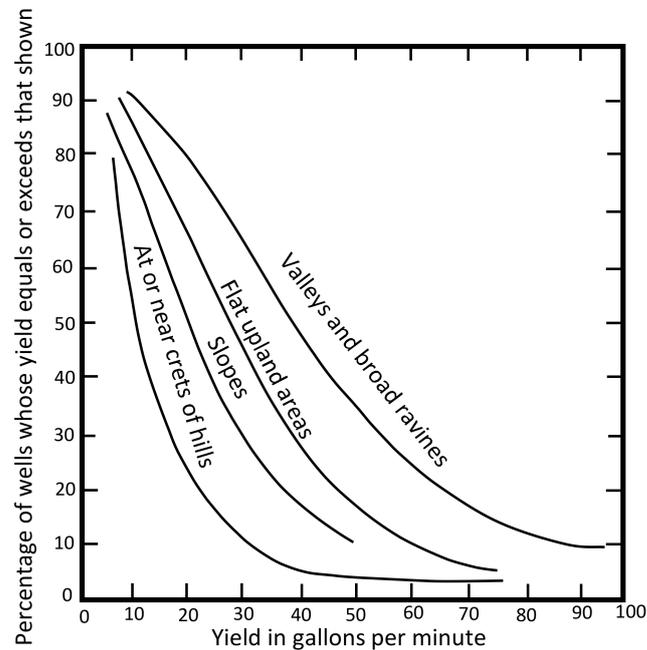


Figure 3. Permeability and hydraulic conductivity of rock units and unconsolidated deposits. Modified from Freeze and Cherry (1979) [3].

The primary permeability is a property directly related to the origin and formation of rock material to allow water to pass through it [42]; likewise, a secondary permeability can be interpreted based on the number and interconnection of structures that are present in a lithological unit [3,43,44]. Although it is true that the hydraulic potential of materials

can be defined by direct and indirect methods—such as petrography, stratigraphy, and resistivity estimation [43]—in this study the permeability was determined based on the characteristics inherent to the formation of the rock (i.e., Figures 3 and 4) and its subsequent fracturing by movements of the earth crust.



**Figure 4.** Relation between landform and potential well yield. Source: Freeze and Cherry (1979) [3] and LeGrand (1954) [45].

It is also presumed that the combination of permeability (primary and/or secondary) with the shape of the terrain is directly related to the potential well yield of a lithological unit (Figure 3). In other words, a portion of materials with a significant primary permeability, such as a smoothed conglomerate hill, is likely to allow water to flow through it easily, as it is composed of elements with varied granulometry and flat topography [6]. In contrast to the above, when it comes to more compact and steeper materials where the speed of surface runoff increases and the spaces between the rock crystals are smaller, the potential well yield of groundwater can be reduced [6].

The combination of the aforementioned factors allowed for the assignment of a groundwater permeability and potential well yield category to each of the elements contained in the TSPA. Categories were based on the aquifer materials, permeability, and hydraulic conductivity to describe how much and how quickly water moves within an aquifer [6].

#### 4. Results

Based on the hydrogeomorphological analysis of the TSPA, a total of 22 units of high, medium, low, very low, and very low/null permeability/potential well yields were characterized (Table 3, Figure 5). The legend of the map is based on [46]. Extensive and highly productive (high aquifer well yield) intergranular aquifer units are shown in shades of blue. The green color range represents fissured environments. The brown areas signify the units of local extension and limited resources, as well as those that are considered to have very low well yield. Alluvial plains, cultivated plains, upper divergent plains, and unconsolidated polymictic conglomerate foothills were identified as intergranular mediums with high permeability and potential well yield.

**Table 3.** Hydrogeomorphologic Units in the Transboundary San Pedro Aquifer.

Recharge/Non-Recharge	Unit	Description
Discharge Zone	High permeability intergranular environment (high potential well yield)	Crop plain
		Upper divergent plain
		Alluvial plain
		Unconsolidated polymictic conglomerate piedmont
	Medium permeability environment (medium potential well yield)	Water
		Unconsolidated polymictic conglomerate hill
		Consolidated polymictic conglomerate hill
	Low permeability environment (low potential yield)	Consolidated polymictic conglomerate and basalt hill
		Fissured limestone, sandstone, and shale hill
	Recharge Zone	Medium permeability fissured environment (medium potential well yield)
Fissured volcanic mountain		
Very low permeability fissured environment (very low potential well yield)		Fissured polymictic conglomerate and volcanic mountain
		Fissured limestone, sandstone, and shale mountain
		Fissured volcanic and sandstone mountain
		Fissured plutonic mountain
		Fissured metamorphic mountain
		Fissured volcanic hill
		Fissured plutonic hill
		Fissured metamorphic hill
Impervious Areas	Urban zone	
	Volcanic hill	
	Plutonic hill	

Regarding the units of medium permeability/potential well yield, only hills of unconsolidated polymictic conglomerate were identified as such. Conglomerate hills, consolidated polymictic conglomerate hills, consolidated basalts, consolidated polymictic conglomerate foothills, consolidated sands, polymictic conglomerate mountains, and polymictic conglomerates were identified as units of limited potential well yield.

The presence of fractures and faults indicates fissured environmental units with a very low permeability and potential well yield. A second subcategory comprises medium permeability fissured units such as fissured limestone, sandstone and shale hill, polymictic conglomerate mountain and fissured sandstone, sandstone mountain, and fissured shale. A third category, the fissured volcanic mountain, was identified in a fissured medium of low permeability and potential well yield. Finally, those units whose permeability is

characterized as very low/null are considered non-aquifer units. According to the flow-direction lines identified for the study area, groundwater flows from south to north and towards the San Pedro River. This information is consistent with Callegary et al. (2016) [24], who also identified cones of depressions near the cities of Sierra Vista, Tombstone, and Cananea. For this study, the hydrological discharge zones were located within the San Pedro River and its tributaries, while the recharge areas were mainly located within mountainous areas: the Huachuca, Mule, and Mustang Mountains (in the United States) and the Sierra Mariquita, Sierra Los Ajos, and Sierra San Jose (in Mexico).

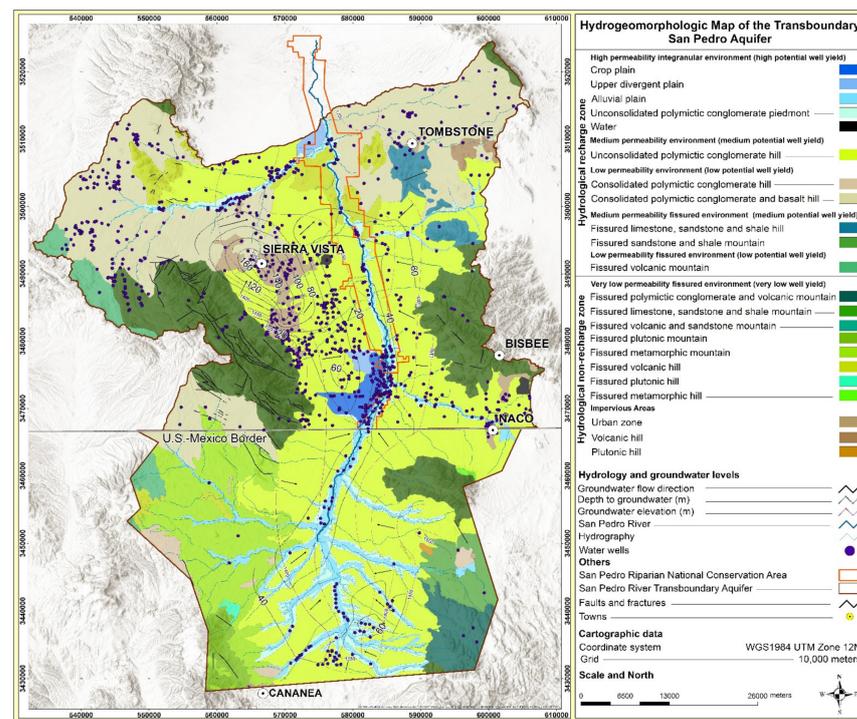


Figure 5. Hydrogeomorphologic map of the San Pedro River Basin.

## 5. Discussion and Conclusions

The TSPA is an aquifer shared between the United States and Mexico. It is also a TAAP aquifer of focus that has been deeply studied over the last decade. The *Binational Study of the Transboundary San Pedro Aquifer* [24] is one of the most relevant binational studies of the region and includes information regarding the physical geography, geology, hydrology, hydrogeology, and geochemistry of the region. According to Chaminé et al. (2015) [18], groundwater characterization must be approached based on different disciplines. These disciplines might include geology, hydrology, hydrogeology, and geochemistry, but also geomorphology and hydrogeomorphology.

Hydrogeomorphology studies describe the interactions between hydrologic processes, landforms, and lithology, and can be useful for determining potential well yields, along with recharge and discharge zones. In this study, we developed a hydrogeomorphologic map for the TSPA. This aquifer is currently experiencing groundwater deficit, with mining, military, domestic, and agricultural users competing for groundwater resources. Hydrogeomorphologic units are defined based on their formation, composition, and original texture of the different rock formations [6]. According to this study, highlands constitute potential recharge zones, and lowlands serve as groundwater-flow discharge areas.

This map makes it possible to quickly identify the functioning of the aquifer system, with the recharge and discharge zones clearly discernible. The information presented here can be used as the basis for the development of sustainable water-resources strategies that consider the hydrogeomorphic characteristics of a given aquifer region to determine how feasible it is to extract or continue extracting water in that area. Moreover, the assessment

of binational aquifers needs to use consistent and harmonized methodologies to identify discharge and recharge areas in need of conservation efforts. The application of this methodology allows the locations of these areas to be identified within the framework of a pragmatic morphogenetic mapping.

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