An integrative approach to sustainable groundwater and associated groundwater-dependent system management in arid karst aquifers: Cuatrociénegas Basin, Mexico

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ABSTRACT The Cuatrociénegas Basin (CCB), Coahuila, Mexico, is a UNESCO Biosphere Reserve with approximately 500 desert springs and associated groundwater-dependent ecosystems (called ciénegas). The reserve protects over 70 endemic species of fish, turtles, mollusks, snails, and other endangered biodiversity, as well as a diversity of globally extremely rare, active freshwater stromatolites. Groundwater development for agriculture in adjacent upgradient valleys threatens spring flow in CCB. Springs vary widely in discharge rate and timing, temperature, and salinity. This study integrates disparate scientific disciplines (i.e., hydrogeology, biology, structure, stratigraphy, geophysics, groundwater modeling) and finds that: 1) spring recharge areas (delineated with a GIS-based chloride-balance water budget approach) combine locally and regionally-derived recharge; 2) gravity profiles show that west CCB springs are fracture controlled (regional aquifer) and east CCB springs are stratigraphically controlled (local and regional aquifer); and 3) groundwater model results show CCB spring flow discharges from both local and regional groundwater flow systems.

Keywords: Arid regions, Groundwater recharge/water budget, Groundwater/surface-water relations, Karst, Water-resources conservation

1. Introduction

Hydrogeologic data are limited temporally and spatially in the Cuatrociénegas Basin of Mexico, which restricts the use of distributed finite-difference or finite-element models to evaluate groundwater management scenarios. In light of the paucity of hydrogeologic data in the region, this paper presents a method for the evaluation of arid karstic aquifer systems and associated groundwater-dependent ecosystems for sustainable groundwater management in developing regions globally. The approach integrates disparate scientific data to generate a system dynamics-based numerical groundwater simulation model. The groundwater model tests hypothesized groundwater flow system providing water to Cuatrociénegas Basin springs and associated groundwater-dependent ecosystems. The model is also used to identify data to be acquired to reduce hydrogeologic conceptual model uncertainty. We present a framework for the characterization of the Cuatrociénegas Basin (CCB,

Fig. 1), Coahuila, Mexico regional arid karst aquifer system and associated groundwater-dependent ecosystems, although this approach can be applied to similar settings globally.

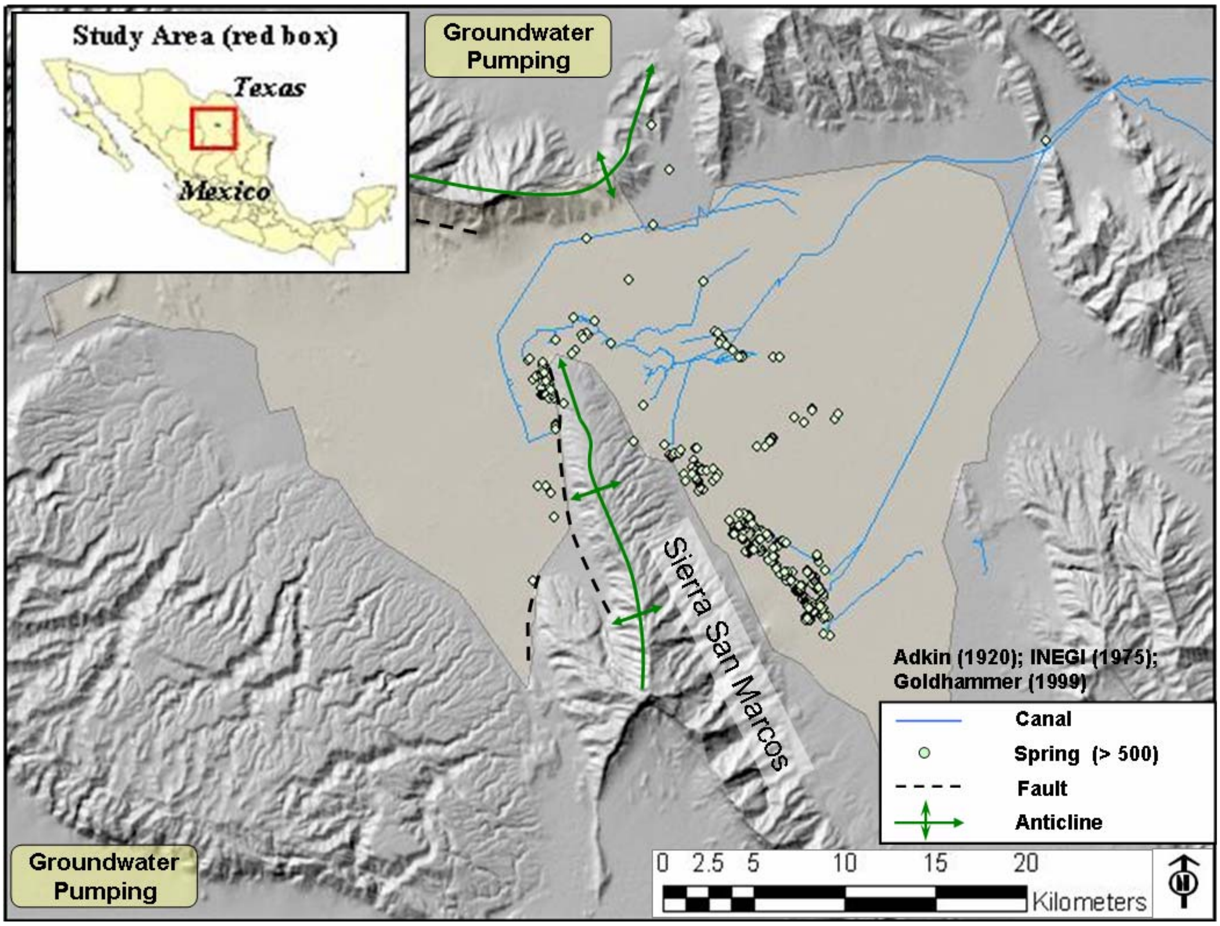

Fig. 1. Cuatrociénegas Basin location and hydrogeology.

2. Background

Water development in the Cuatrociénegas Basin region has substantially reduced groundwater-dependent ecosystem size. The formerly closed basin included large playa lakes and extensive ciénega ecosystems. Natural discharge from the Cuatrociénegas Basin was evapotranspiration and possibly surface and groundwater outflows, but interbasin surface or groundwater flow to the La Madrid Valley to the east is not historically documented (see Fig. 2 for place names). ^{14}C dating indicate at least 30,000-year old groundwater-dependent ecosystems in the Cuatrociénegas Basin (Meyer, 1973). Archeological remains in caves show that humans fished valley wetlands since pre-Columbian times. Spaniards settled the Cuatrociénegas Basin in the 1760s, attracted by the spring-fed Río Cañon, which they used to irrigate gardens, orchards, and vineyards.

Now, canals convey spring discharge out of the formerly closed basin through the Puerto Salado gap to irrigate the La Madrid Valley. French drains lowered shallow groundwater for grazing, reduced wetland size, and dried unique freshwater stromatolites associated with the former Río Garabatal in the western Cuatrociénegas Basin. Groundwater level was close to the ground surface in the 1970's in upgradient valleys to the north and south, prior to large-scale agricultural groundwater development for alfalfa in the mid-1980s, that caused over 20 m drawdown in the Hundido Valley to the south and drying the Río Cañon to the north. In the 1960s, this spring discharge was approximately 0.25 m^3/sec; now the Río Cañon rarely flows (Minckley, 1969).

In light of the adverse environmental effects of water development projects, wetland restoration is occurring. Pronatura Noreste, a Mexican non-governmental conservation organization, has purchased water rights from farmers to restore wetlands – the first such purchase in Mexico. Reserve managers are also exploring the possibility of diverting canal flow through the now dry Río Garabatal to restore wetlands. Currently, continued groundwater over-exploitation in upgradient basins to the north, west, and south basins threatens spring-fed wildlife habitat in the Cuatrociénegas Basin. In light of the threat to Cuatrociénegas Basin spring flow from pumping, this paper presents an approach for evaluating arid karstic aquifer systems in support of sustainable groundwater development.

3. Methods

It is difficult to evaluate the effects of groundwater mining in surrounding valleys on Cuatrociéngas Basin springs because their recharge area is uncertain. We integrate disparate data sources (that are limited when considered alone) to improve the hydrogeologic conceptual model so that a groundwater model can be used to assess pumping effects on spring flow.

3.1. Hydrogeologic Data

Hydrogeologic data in the Cuatrociénegas Basin are limited. Long term groundwater level and water quality do not exist, and are only available for discrete sampling events of limited duration. As a result, we integrate disparate hydrogeologic data, including precipitation, and spring geochemistry, stable isotopes (Sr, O, and H), temperature, and discharge. When the entire data suite is evaluated, hydrogeologic conceptual model uncertainty is reduced substantially. Andring et al. (2006) compile geochemical data of groundwater from 76 wells and 27 springs collected by Rodríguez et al. (2005) and Evans (2005) during spring and summer 2004. Spring discharge is recorded using flow meters in canals and selected springs starting in January 2003 to understand trends in spring discharge. Precipitation is recorded starting June 2004 and spring temperature data is recorded during summer 2004 in Poza La Becerra (the largest spring in the west sub-basin) and Poza Santa Tecla in the east sub-basin in order to gain insight on the origin of recharge to springs. Sr isotopic analyses from 18 spring water samples and two travertine samples help us understand the age of aquifer material through which groundwater has flowed from recharge to discharge sources. Stable O and H isotopes of from spring and well water (Rodríguez et al., 2005; Johannesson et al., 2004) provide insight into recharge elevations.

3.2. Gravity Surveys

Surface gravity surveys are conducted along transects perpendicular to lines of springs to infer subsurface geologic controls on spring locations. Jansen et al. (2004) conducted gravity surveys in Death Valley (a similar carbonate terrane) to infer carbonate subsurface topography.

3.3. GIS Catchment Delineation

In order to understand Cuatrociénegas Basin spring recharge sources, groundwater catchments are delineated based on surface topography using geographic information systems (GIS) for an approximately 97,000 km^2 upgradient area. GIS delineate catchments using 100-m^2 digital elevation models (DEMs, 700 to 3,025 m; Maidment, 2002). A Cl-balance approach estimates recharge (Dettinger, 1989):

$$\text{Recharge} = P\,(Cl_p / Cl_{spr}) \quad (1)$$

Where: P = precipitation (mm), Cl_p = precipitation chloride concentration (mg/L), Cl_{spr} = spring water chloride concentration (mg/L). An analytical flow model evaluates interbasin groundwater flow (Jacob, 1943):

$$h(x)=\sqrt{h_1^2+\frac{(h_2^2-h_1^2)}{L}x+\frac{W_s}{K}\left(\frac{L}{2}\right)^2-\frac{W_s}{K}\left(x-\frac{L}{2}\right)^2} \quad (2)$$

Where: h(x) = hydraulic head (m) at any point x (m), h_1 and h_2 = heads (m) on either side of a topographic divide separated by length L (m) comprised of an unconfined aquifer with a hydraulic conductivity K (m/s), and with constant recharge W_s (m).

3.4. Hydrogeologic Conceptual Model

Structural and stratigraphic data (Lehmann et al., 1999; Goldhammer, 1999) are used to evaluate the aquifer through which groundwater flows from recharge areas to springs discharge areas.

3.5. Groundwater Model

A numerical groundwater simulation model is created to test working hypotheses of the hydrogeologic conceptual model. Tidwell et al. (2004) describe the method for creating a spatially aggregated physical process model within a systems dynamics framework. The model follows the water budget (all units = m^3/time):

dS/dt = Recharge + groundwater in – groundwater out – pumping – spring flow (3)

The model permits flow between adjacent cells in an unconfined carbonate and alluvial aquifer according to Darcy's Law (modified to account for harmonic mean of hydraulic conductivity):

$Q = (K_1 K_2 dh\, dy\, dz) / (K_2 dx_1 + K_1 dx_2)$ (4)

Where: K_1 and K_2 = hydraulic conductivity (m/s) of adjacent cells, dh = head difference (m), dy and dz = cross-secitonal area to flow (m^2), and dx_1 and dx_2 = distance (m) between centroids of two adjacent cells (m). A hypsometric curve estimates spatially-distributed precipitation based on average elevation:

Precipitation (m/yr) = 0.000097(1/yr) x (elevation, m) + 0.146989 (m/yr) (5)

Recharge equals spring discharge measured by this study (although actual recharge is probably higher). The model is calibrated by varying hydraulic conductivity (based on analogous karst terranes) to observed heads for two cases (all local recharge vs. a combination of local and regional recharge) with constant recharge and spring discharge.

4. Results And Discussion

This research creates a constrained numerical model of the hydrogeologic system that Mexican reserve managers can ultimately use for management scenario analyses to understand effects of various pumping and climatic scenarios on spring discharge.

4.1 Hydrogeologic Data

An evaluation of geochemistry data shows that spring water electrical conductivity ranges from 2,360 to 2,550 micro Siemens (μS) in west sub-basin springs and is approximately 1,400 μS in east sub-basin springs. The freshest groundwater (probably from local recharge) is located in wells and springs of the eastern-most Cuatrociénegas Basin on the flanks of the Sierra Purísima and in Ocampo Valley wells. Groundwater becomes progressively higher in SO_4 and Cl from wells in the Hundido Valley on the flank of the Sierra Alamitos to Hundido Valley irrigation wells to Cuatrociénegas Basin source and resurgent springs. Spring water is predominantly Ca-SO_4 facies (reflecting carbonate and evaporite rocks), although the freshest waters are Ca-HCO_3 facies.

Temperatures in Poza Santa Tecla, an east sub-basin spring, vary diurnally (approximately 0.5°C) and decreases from approximately 30.55°C to approximately 28 and 24°C in response to two storms totaling approximately 2 cm precipitation during the summer 2006 monsoon (Wolaver and Sharp, 2007, in press), suggesting a combined local and regional flow component. Temperature in Poza La Becerra, a west sub-basin spring (and the largest spring in the Cuatrociénegas Basin, Q_{avg}=580 L/s), remains stable and is elevated at approximately 34°C during precipitation events. In other carbonate terranes, stable and elevated spring temperatures indicate deeper, regional groundwater flow systems. For comparison, average ambient temperatures range between 16°C (air, Rodríguez et al., 2005) and 20°C (shallow groundwater, Collins, 1925).

Spring discharge in the Santa Tecla Canal (which collects discharge from numerous springs in the east sub-basin) decreased during an approximately four-year period of record (Q=220 L/s to

Q=180 L/s). This suggests that east sub-basin springs vary in response to a regional drought or decreasing in response to pumping in adjacent basins. In the west sub-basin, Poza La Becerra discharge essentially remains stable (Q_{avg}=580 L/s), indicative of a regional aquifer system source that is less susceptible to climatic or pumping perturbations.

Sr isotopic analyses of spring waters and travertine are homogeneous (all samples range between 0.707425 and 0.707490 $^{87}Sr/^{86}Sr$). When these results are compared to $^{87}Sr/^{86}Sr$ of rocks collected by Lehmann et al. (1999) the best fit matches rocks of the Acatita and Aurora Formation (between approximately 106 to 99 ma). These carbonate and evaporate rocks are found throughout the study area and may represent a karstic aquifer that conveys a regional flow component to Cuatrociénegas Basin springs.

Rodríguez et al. (2005) use stable isotopes (O and H) to suggest that recharge occurs in the mountains surrounding the Cuatrociénegas Basin. Johannesson et al. (2004) finds that recharge occurs at elevations corresponding to mountains in the study area, but cannot distinguish exactly which mountains the recharge occurs, as mountain elevations are similar throughout northeast Mexico.

4.2. Gravity Surveys

Results of surface gravity geophysical surveys indicate that fault-associated fractures are the primary mechanism to convey water from a regional aquifer to springs in the west sub-basin. In the east sub-basin, stratigraphically controlled conduits convey local and regional recharge to springs. Hypothesized fault and fold control on these springs was discounted by gravity profiles.

4.3. GIS Catchment Delineation

Groundwater catchments delineated in GIS suggest that during past pluvial periods, surface water could have flown from the Río Nazas drainage through the Cuatrociénegas Basin to the Río Grande (Fig. 2, following page). Cl-balance recharge analyses suggests a 18,300 km^2 area of four upgradient valleys (1,663 to 6,651 km^2, Fig. 2, numbers 3 to 6) contributes recharge to Cuatrociénegas Basin springs.

4.4. Hydrogeologic Conceptual Model

Hydrogeologic data, geophysical surveys, and GIS-delineated catchments are integrated to create a hydrogeologic conceptual model with springs of two distinct hydrogeologic characters: primarily locally- (east sub-basin) and regionally-derived (west sub-basin) recharge (Fig. 3).

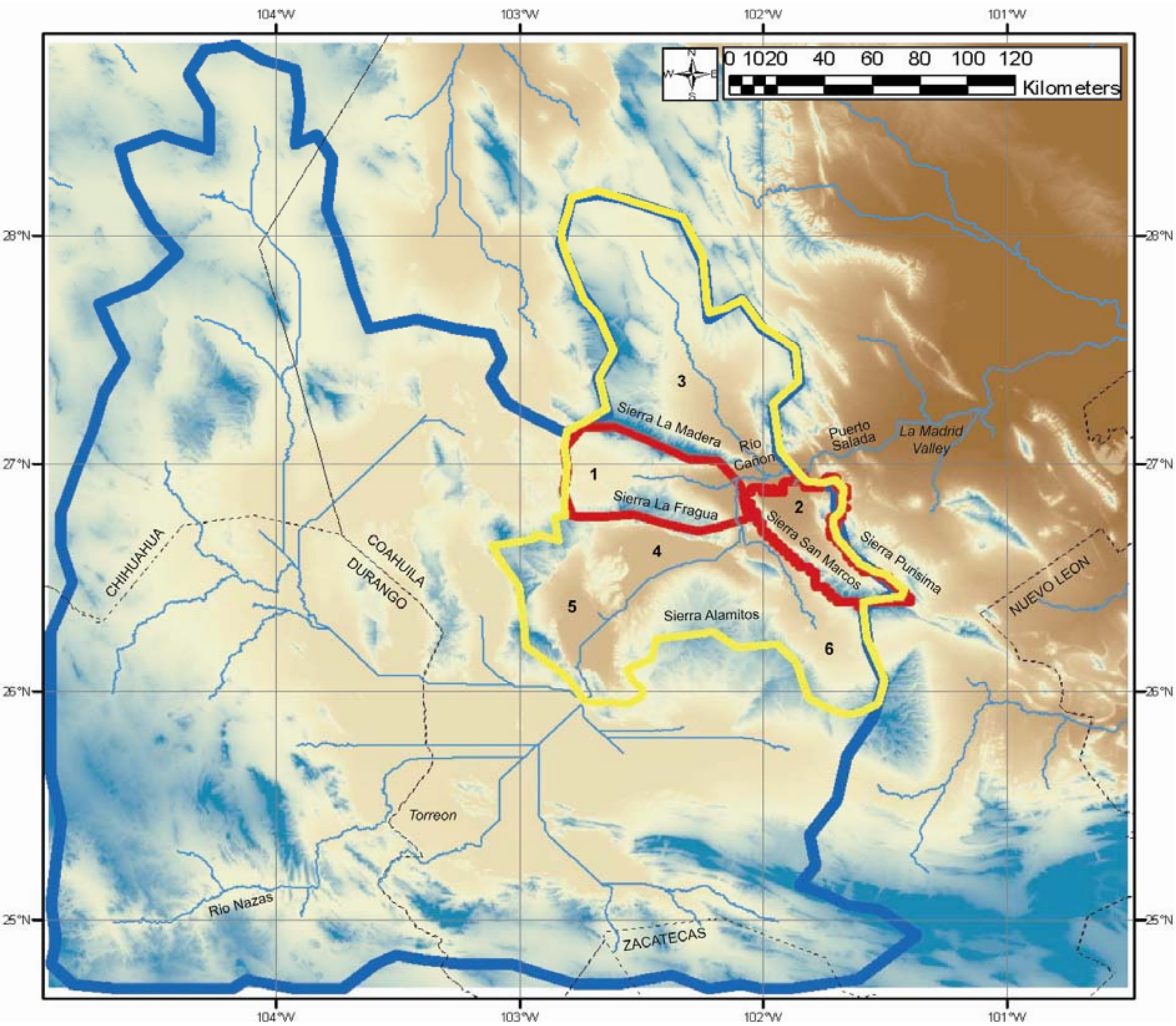

Fig. 2. Catchments (elevation: high = green, low = brown). Basin names: 1 = Cuatrociénegas west sub-basin, 2 = Cuatrociénegas east sub-basin, 3 = Ocampo Valley, 4 = Hundido Valley, 5 = Sobaco Valley, 6 = San Marcos Valley. Thick blue line = 97,000 km^2 catchment upgradient to the Cuatrociénegas Basin. Yellow = most likely recharge area based on Cl-balance recharge calculations. Thin blue lines = inferred drainage (presently, the Rio Nazas dries at Torreón; historically, the Río Cañon only flowed into the Cuatrociénegas Basin; the Cuatrociénegas basin was historically closed – now canal discharge flows through the Puerto Salado gap to irrigate crops in the La Madrid Valley. Dotted black lines = state borders (labeled in capital letters).

4.5. Groundwater Model

Groundwater model results show that Cuatrociénegas Basin spring flow discharges from both local and regional groundwater flow systems. This is demonstrated by model calibration problems under strictly local recharge scenarios and other data (temperature, discharge, salinity). Thus, pumping in adjacent valleys may threaten spring discharge and associated groundwater-dependent ecosystems. Groundwater model uncertainty, because of limited data, is constrained by integrating different hydrogeologic data sets. Temperature and geochemistry modeling is planned to reduce uncertainty.

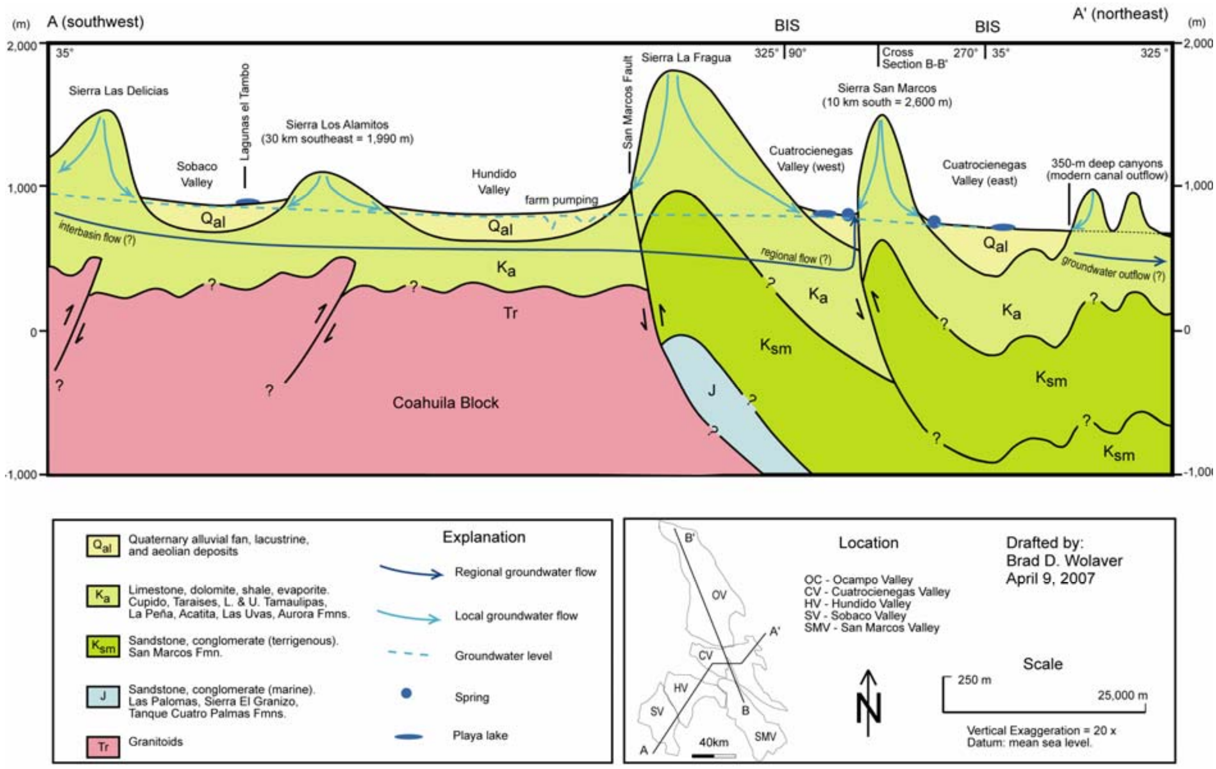

Fig. 3. Hydrogeologic conceptual cross section.

5. Conclusions

This research presents a framework for arid karstic aquifer system and associated groundwater-dependent ecosystems evaluation that integrates hydrogeologic and other data sets. These indicate that Cuatrociénegas Basin spring flow is derived from a combination of local and regional recharge. Stratigraphically controlled conduits convey local and regional groundwater to some springs, while fault-associated fractures convey water from a regional aquifer to other springs. Thus, pumping in adjacent valleys may adversely impact spring discharge in the Cuatrociénegas Basin. We recommend the installation of a monitoring well network away from pumping centers in upgradient basins and the management of agricultural pumping to maintain heads higher than spring elevations. Additional temperature and geochemistry modeling is planned to reduce hydrogeologic conceptual and numerical model uncertainty. Ultimately, the procedures developed by this research will present Mexican water resource managers with the information needed to develop effective water management policies to protect Cuatrociénegas Basin groundwater-dependent ecosystems from unsustainable development. This approach is developed for the Cuatrociénegas Basin; however, it can be applied to similar locations globally.

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