ground water

Delineation of Regional Arid Karstic Aquifers: An Integrative Data Approach

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Abstract

This research integrates data procedures for the delineation of regional ground water flow systems in arid karstic basins with sparse hydrogeologic data using surface topography data, geologic mapping, permeability data, chloride concentrations of ground water and precipitation, and measured discharge data. This integrative data analysis framework can be applied to evaluate arid karstic aquifer systems globally. The accurate delineation of ground water recharge areas in developing aquifer systems with sparse hydrogeologic data is essential for their effective long-term development and management. We illustrate the use of this approach in the Cuatrociénegas Basin (CCB) of Mexico. Aquifers are characterized using geographic information systems for ground water catchment delineation, an analytical model for interbasin flow evaluation, a chloride balance approach for recharge estimation, and a water budget for mapping contributing catchments over a large region. The test study area includes the CCB of Coahuila, Mexico, a UNESCO World Biosphere Reserve containing more than 500 springs that support ground water–dependent ecosystems with more than 70 endemic organisms and irrigated agriculture. We define recharge areas that contribute local and regional ground water discharge to springs and the regional flow system. Results show that the regional aquifer system follows a topographic gradient that during past pluvial periods may have linked the Río Nazas and the Río Aguanaval of the Sierra Madre Occidental to the Río Grande via the CCB and other large, currently dry, upgradient lakes.

Introduction

This research develops procedures for delineation of regional ground water flow systems in arid karstic aquifers with sparse hydrogeologic data and estimation of regional arid karstic aquifer recharge based on observed spring discharge. We apply this approach to delineate regional ground water flow systems in the Cuatrociénegas Basin (CCB) region of northeast Mexico (Figure 1). This framework for aquifer characterization in developing arid regional karstic aquifers is important because resource managers must understand the spatial extent of regional ground water flow systems to use these ground water systems in a sustainable manner globally.

This aquifer evaluation approach overlaps with earlier assessment methods, such as those used to delineate regional arid karstic aquifer systems in the Great Basin (Maxey and Eakin 1949; Eakin 1966; Maxey 1968; Eakin et al. 1976; Winograd and Thordarson 1975; Mifflin 1988). New technologies presented here augment and expand upon previously described approaches. Hall et al. (2005) describe the first global high-resolution (3 arc-s) digital elevation model (DEM). This DEM produced by NASA's shuttle radar topography mission (SRTM) is available for 80% of the Earth's landmass (60°N to 50°S). The SRTM data set is particularly valuable for developing regions where accurate elevation surveys may not have

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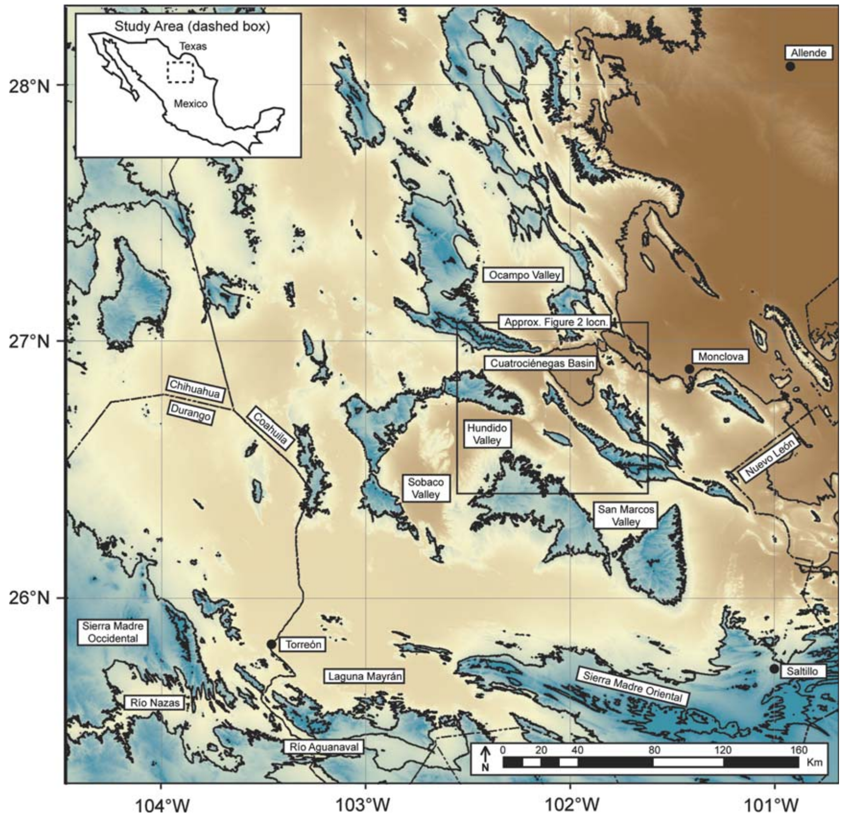

Figure 1. CCB study area. Contour interval ranges from brown (750 m) to green (1500 and 2250 m). State boundaries are indicated by dashed lines.

been available for regional hydrogeologic evaluations, such as the earlier Great Basin studies. Recent hydrologic advances in geographic information systems (GIS; Tarboton 1997; Maidment 2002) permit rapid evaluation of these high-resolution DEMs, facilitating the topographic basin analysis approach of Eakin (1966) to delineate ground water catchments based on surface topography. Also, hydrogeologic parameters like precipitation and recharge can be spatially distributed in GIS efficiently, aiding the recharge evaluation approach of Maxey and Eakin (1949). We also use GIS to evaluate recharge using the chloride balance water budget approach (Dettinger 1989).

Using this integrative data approach for arid aquifer characterization, we test the hypothesis that significant flow to CCB springs (Figure 2) originates from recharge from catchments external to CCB. We delineate ground water catchments associated with surface water catchments contributing to CCB spring flow based on surface topography using a combination of remotely sensed digital elevation data of surface topography, geologic information, an analytical model for interbasin flow determination, chloride balance recharge estimation using a water budget approach, and an evaluation of environmental isotopes. Upgradient catchments are sequentially included in a regional ground water flow system until calculated recharge equals observed spring discharge. We find that CCB spring discharge cannot all be locally derived and that a regional flow system provides significant water.

Background

The CCB is located in a complex geologic setting. Subsequently, we discuss the structural, tectonic, hydrostratigraphic, and hydrogeologic setting of CCB and surrounding region. We compare CCB with similar regional arid karstic aquifer systems where interbasin flow occurs.

Structure and Tectonics

The CCB is located at the northern edge of the highly folded and faulted Sierra Madre Oriental. Goldhammer (1999) described Upper Triassic to Late Middle Jurassic stratigraphy of northeastern Mexico. Lehmann et al. (1999) correlate Cretaceous carbonate mountain anticlines surrounding CCB with rocks in Texas. Murillo (1997) notes that the Lower Cretaceous Cupido Formation, which crops out in CCB, is the equivalent of the Sligo Formation of Texas.

Goldhammer (1999) describes rifting associated in northeast Mexico associated with the opening of the Gulf of Mexico that created basement highs (e.g., Coahuila Platform). These permitted shallow water marine carbonate deposition and lows (e.g., the Sabinas Basin located ~125 km northeast of CCB) that resulted in passive margin accumulation from the Upper Jurassic to the Early Upper Cretaceous.

Antunano (2001) quantifies Sabinas Basin marine sediment accumulation more than 5000 m in three supersequences: (1) synriftal sediments of primarily conglomerates and evaporates; (2) high-frequency cycles of

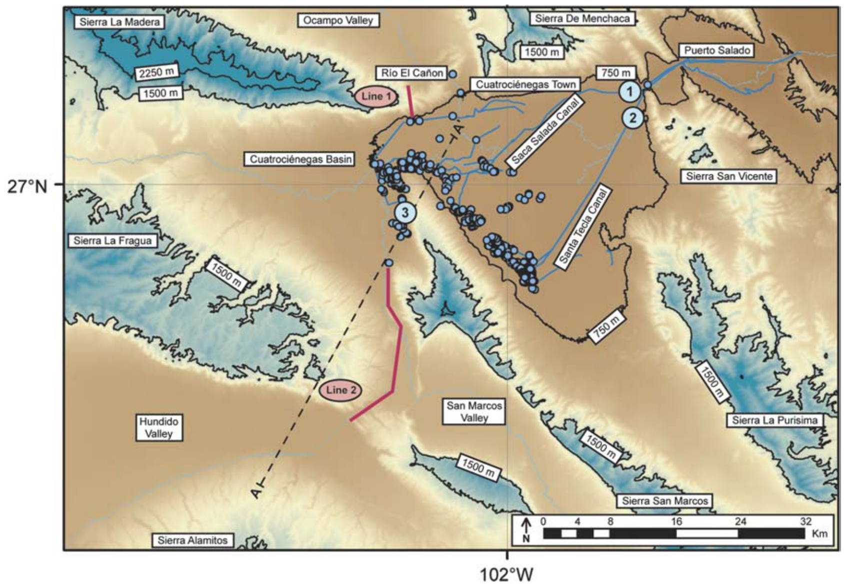

Figure 2. CCB features include springs (blue dots), analytical model locations (red lines), canals (light blue lines), discharge measurement locations (light blue numbered circles), inferred surface drainage network (light blue dashed line), and 750-m contour intervals (low- to high-elevation ranges from brown to green, respectively). The location of cross section A to A′ (Figure 3) is shown as a dashed black line.

carbonates, evaporates, and coastal siliciclastics deposited on extensive platforms on a passive margin (144 to 96 million years ago [Ma]); and (3) regressive terrigenous clastic facies deposited in a foreland setting (96 to 39.5 Ma).

Hydrostratigraphy

Evans (2005) describes the stratigraphy in CCB as primarily Jurassic and Cretaceous Age carbonates, evaporites, and sandstone overlying a Permo-Triassic granodioritic basement. Lesser y Asociados (2001) and Rodriguez et al. (2005) present a hydrogeologic conceptual model for CCB and adjacent valleys that includes parallel mountain anticlines and synclines filled with alluvium and lacustrine sediments (Figure 3). Highlands are dominated by Cretaceous carbonates, and intermontane basins are filled with alluvial fan, playa, and lacustrine sediments. Mountains surrounding CCB and the valley-fill alluvium both display a high degree of karstification (Badino et al. 2004). Wolaver et al. (2005) calculated recharge on the 870 km^2 intrabasin recharge area that both Lesser y Asociados (2001) and Rodriguez et al. (2005) suggest produces all CCB spring discharge. The recharge calculations generated only 0.215 Mm^3 discharge compared with observed 35 Mm^3 and indicated interbasin ground water flow. Johannesson et al. (2004) identified high-elevation recharge zones from stable isotopes but did not identify in which catchments recharge occurs.

Lehmann et al. (1999) use strontium isotopes and biostratigraphy to determine that the Cretaceous carbonate rocks that form the uplands and underlie valley-fill alluvium are late Barremian to late Albian in age. Lehmann et al. also describe lime mudstones (Cupido), shale and lime mudstones (La Peña), lime mudstones and intercalcated wackestones/packstones, dolomitized grainstones, shallow subtidal to peritidal carbonates, shales, and lime mudstones (Aurora) overlain by more deep water

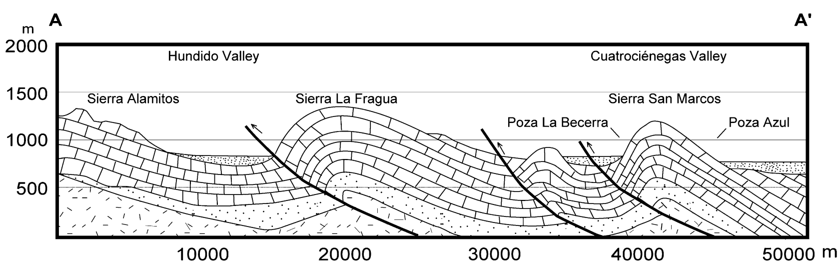

Figure 3. Generalized geologic cross section from the Hundido Valley to the CCB through the Sierra La Fragua and Sierra San Marcos (after Rodriguez et al. 2005). Orientation of geologic cross section is from south-southwest to north-northeast crossing the Sierra San Marcos and associated springs (see Figure 2 for location of cross section). Cretaceous carbonate rocks (block pattern) and Cretaceous terrigenous siliciclastics (coarse-stippled pattern) underlie Quaternary valley-fill alluvium (fine-stippled pattern) throughout the study region. The regional basement comprises Permo-Triassic granitoids (dashed pattern). Arrows indicate the relative motion of multireactivated thrust faults that bound many of the anticlinal structures in the region.

laminates (Cuesta del Cura) in the nearby Sierra de Parras. Badino et al. (2004) describe the highly karstified nature of the carbonate rocks present in the CCB region.

Meyer (1973) collected sediment cores in CCB. Radiocarbon dating in the ground water–dependent ecosystems yields dates of at least 30,000 years before present. Alluvial fans are present primarily on the eastern flank of the Sierra San Marcos. Badino et al. (2004) describe lacustrine and playa lake valley-fill alluvium; they noted that evaporation of spring water from Poza El Churince precipitates gypsum and has produced the second largest white sand dune complex in North America. Evans (2005) and Minckley (1969) describe the valley-fill alluvium as highly karstified with sinkholes and re-emergent springs toward the center of the valley. Minckley and Cole (1968) note that total dissolved solids of these terminal lakes approaches 300,000 mg/L. Prior to the construction of canals, which now drain the valley, CCB was a closed basin with large playa lakes dominating the eastern half of the valley. Miele et al. (2000) used magnetotelluric soundings to determine that carbonate anticline mountains continue in the subsurface, and Rodriguez et al. (2005) estimate an average CCB alluvium depth of 200 m using time domain electromagnetics. Table 1 presents a generalized hydrostratigraphic column of CCB.

Ground Water Resources and Hydrogeology

Irrigation pumping of ground water commenced in the mid-1900s, which caused ground water level declines of tens of meters in the neighboring Hundido and Ocampo valleys (Figures 1 and 2). Interbasin spring-fed streamflow (historically 0.25 m^3/s; Minckley 1969) from the Ocampo Valley has decreased; the Río Cañon now only intermittently flows into CCB, and interbasin ground water flow may have also decreased (Hendrickson 2005; Minckley 1969; Rodriguez 2005; Rodriguez et al. 2005). Continued regional ground water resource development may further decrease spring discharge.

Spring discharge is generally too saline for potable use, and abundant spring discharge has been conveyed into canals for irrigation in lieu of ground water production wells. As a result, transmissivity data are sparse. Comparisons of aquifer properties shown in Table 2 are drawn from analogous karstic terrains in Texas and Nevada, where interbasin ground water flow is created by high transmissivity carbonate rocks similar to those of the CCB region.

Recharge Processes in CCB and Analogous Regions

Possible recharge mechanisms in CCB include (1) direct recharge on fractured carbonate mountain highlands where precipitation may be as much as 400 mm/year (González 2006); (2) limited recharge of mountain-front runoff on calichified alluvial fans; (3) recharge in valley floors where precipitation averages approximately 219 mm/year (Rodriguez et al. 2005); and (4) interbasin flow.

Recharge is calculated as follows:

$$\text{Recharge} = \text{Precipitation} - \text{Evapotranspiration} - \text{Surface runoff} \quad (1)$$

Spatially distributed evapotranspiration is extremely difficult to calculate in arid karstic aquifers without an array of meteorological stations. However, insights can be drawn from scientific literature on the estimation of recharge as a function of precipitation in analogous regions (i.e., West Texas and Nevada). Recharge in CCB

Table 1
Generalized Hydrostratigraphic Column

Age	Formation	Description	Permeability
Quaternary	Alluvium	Sand, gravel, lake deposits, evaporate deposits, travertine	Variable
Cretaceous	Eagle Ford	Limestone, shale	Low
	Buda	Limestone, interbedded sand and gravel	Low
	Del Rio	Clay, sandy limestone	Low
	Georgetown (Cuesta del Cura)	Limestone	Moderate
	Washita Group	Limestone	Moderate
	Kiamichi	Limestone, shale	Low
	Auroroa	Lime mudstones and wackestones, gypsum, dolomitized grainstones	High
	La Peña	Dark laminated shale, thin lime mudstone interbeds	Low
	Cupido	Lime mudstone	High
	La Virgen	Gypsum, dolomite, limestone, shale, clay	Low
	La Mula	Shale, sandstone, limestone, conglomerate	Low
	La Padillla	Massive dolomite, interbedded shale, sandstone, evaporites	Low
	San Marcos	Sandstone, hematitic cement, interbedded conglomerate	Low to moderate
Permo-Triassic	Basement	Granodiorite	Low

Note: Modified from Evans (2005), Rodriguez and Sanchez (2000), McKee et al. (1990), and Lesser y Asociados (2001).

Table 2
Permeability for Carbonate Terrains in Texas, Nevada, and Mexico

Reference	Location and Rock Type	Hydraulic Conductivity (m/d)	Transmissivity (m^2/d)[1]
Bedinger et al. (1986)	Great Basin, southwest United States, dense to moderately dense carbonate	5×10^{-4} to 8×10^{-1}	*1.1×10^{-2} to 1.8×10^{1}*
	Great Basin, southwest United States, fractured, karstic carbonate	1×10^{-1} to 1×10^{4}	*2.3×10^{1} to 2.3×10^{5}*
Uliana (2000)	West Texas, United States, Apache Mountains, Permian carbonate reef facies	—	6×10^{-5} to 3×10^{-4}
Nielson and Sharp (1985)	West Texas, United States, Dell City, Bone Spring-Victorio Peak limestones	—	9.3×10^{2} to 3.1×10^{3}
Mace et al. (2004)	Central Texas, United States, Coahuila, Mexico Edwards-Trinity Aquifer	9.0×10^{-4} to 2.2×10^{2}	1.5×10^{-1} to 2.5×10^{4}
Rodriguez et al. (2005)	CCB, Coahuila, México Carbonate	1.9×10^{1}	*4.3×10^{2}*

[1]Hydraulic conductivity (m/d) values from the literature are converted to transmissivity (shown in italics), assuming a saturated thickness of 22.5 m, based on an average saturated thickness from analytical model inputs subsequently.

region is also estimated using the chloride mass balance method (Dettinger 1989; Anderholm 2000; Wolaver et al. 2005). The hypothesized regional ground water catchments are considered verified when measured canal discharge equals calculated recharge.

Recharge in Other Semiarid Areas

In West Texas, a complexly faulted karstic aquifer is overlain by alluvium (recharge estimates for West Texas are summarized in Table 3). Gates et al. (1980) estimate recharge from local precipitation ranging from a low of approximately 183 mm/year (elevation of 1119 m above mean sea level [amsl] at Ysleta, Texas, near El Paso) to a high of approximately 476 mm/year (elevation of 2000 m at Mt. Locke in the Davis Mountains). They suggest that recharge occurs in foothills surrounding valley-fill aquifers, in plateaus where sediments are coarse grained, and in ephemeral stream channels during high precipitation events. Gates et al. (1980) comment that regardless of the mechanism, recharge probably does not occur unless precipitation is great enough so that surface flow occurs. Contrary to Gates et al. (1980), Hibbs and Darling (2005) find that low-permeability late-stage calcic soils like those in CCB limit recharge on alluvial fans (Figure 4). Based on environmental isotope data (e.g., high radioactive tritium activities from 0.5 to 3.0 tritium units and 40% to 50% modern carbon in ^{14}C in shallow upper mountain wells) originally published by Darling et al. (1994), higher recharge rates occur in mountainous areas. Van Broekhoven (2002) found that upland fractures contribute significant subflow to valley-fill aquifers.

Maxey and Eakin (1949) and Eakin (1966) assessed recharge and ground water flow in the White River Valley of Nevada, an aquifer system with interconnected valley-fill basins overlying Paleozoic carbonates. Eakin and Moore (1964) investigated the uniformity of discharge at Muddy River Springs at the end of the White River flow system and noted that large springs with uniform

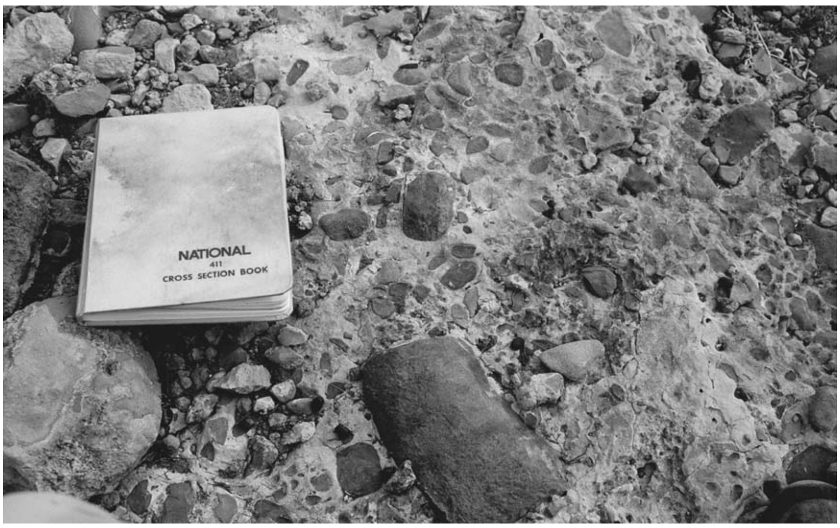

Figure 4. Caliche layer in an alluvial fan on the east side of the Sierra San Marcos limits ground water recharge.

Table 3
Recharge as a Percentage of Precipitation in West Texas

Reference	Location	Elevation (m amsl)	Precipitation (mm)	Recharge as Percent of Precipitation
Gates et al. (1980)	West of Pecos River	—	294	1.00[1]
	Ysleta, Texas	1119	183	
	Mt. Locke, Davis Mountains	2000	476	
	Hueco Bolson	—	254	1.00
Meyer (1976)	Hueco Bolson	—	254	0.95
Darling (1997)	Red Light Basin	—	225[2]	0.60
Nielson and Sharp (1985)	Wildhorse Flat	—	—	1.00

[1]Gates et al. (1980) and Meyer (1976) estimate recharge in West Texas at 1% of annual precipitation for all elevations.
[2]Based on a recharge rate of 0.18 cm/year and 0.6% of precipitation recharged, limited to a recharge area of only 20% of the overall landscape.

discharge (such as those in the CCB) are indicative of regional flow systems with distant recharge areas. Tyler et al. (1996) analyzed stable isotopes of oxygen and deuterium and soil water chloride to infer that recharge in Nevada occurs only in the mountain fronts and basin margins, not in lower elevation valley fill. Table 4 summarizes recharge as a percentage of precipitation in Nevada.

Considering these analogous areas, we infer that valley floor recharge in CCB may be quite low (approaching 0% of precipitation), while mountain recharge is higher (~3% to 7%), resulting in an overall recharge rate well under 5% (perhaps as low as 1%) of precipitation when regional elevation is considered.

Recharge in the CCB

Field observations show that alluvial fans on the slopes of the Sierra San Marcos are heavily calichified. In addition, a caliche layer at a depth of approximately 0.3 m on the west side of the Sierra San Marcos and in the floor of the unlined Saca Salada canal in the northeast corner of the basin (Figure 2) suggests that recharge is limited in the valley floor by a thick caliche layer similar to that reported in West Texas by Hibbs and Darling (2005).

Rodriguez et al. (2005) present carbon-14 age dates of ground water from wells in the Hundido Valley; wells and springs in CCB were also analyzed. The results of corrected age dates (despite one analysis from a terminal lake with 119% modern carbon) suggest ground water ages from approximately hundreds of years (at the northern flank of the Sierra Alamitos in the eastern Hundido Valley) to 17,000 years (at the northeastern corner of the Hundido Valley). Many corrected ages in both the Hundido Valley and the CCB range between 7000 and 10,000 years. One sample from a spring travertine deposit at the southwest corner of the basin has a carbon-14 age of approximately 17,000 years.

Carbon-14 age analyses from well water in the center of the Hundido Valley, spring discharge, and travertine suggest that increased recharge may have occurred during a past period of wetter climate. In the eastern CCB at the northern flank of the Sierras Purísima and Vicente and at the base of the Sierra La Madera, percent modern carbon more than 40% suggests moderate-to-high recharge rates (Hibbs and Darling 2005). Lower percent modern carbon values from wells in the center of the Hundido Valley and most CCB source springs suggest lower recharge rates consistent with the findings of Hibbs and Darling (2005). Thus, direct recharge in mountain highlands (as in

Table 4
Recharge as a Percentage of Precipitation in Nevada

Reference	Location	Elevation (m amsl)	Precipitation (mm)	Recharge as Percent of Precipitation
Eakin (1966)	White River	>1800	>508	25
	Valley	<1800	<508	~0
Eakin et al. (1976)	Great Basin	—	—	5
Tyler et al. (1996)[1]	NTS	High	High	Yes[1]
		975	124	No recharge
Maxey and Eakin (1949)	White River Valley	—	>508	25
		—	381–508	15
		—	305–381	7
		—	204–305	3
		—	<204	0

Note: NTS = Nevada Test Site.
[1]Recharge at the NTS does not occur at valley floor at current arid climatic conditions and is limited to higher elevations.

Nevada and West Texas) may be the primary recharge mechanism in CCB with minimal recharge on the valley floors approaching 0% of precipitation.

Springs: CCB

Adkins (1920) conducted the earliest hydrogeologic assessment. He inferred that faults influence the linear trend of dozens of springs on either side of the Sierra San Marcos anticline (Figure 2). Minckley and Cole (1968) describe spring water chemistry from an aquatic biology perspective, and Evans (2005) defines ground water flowpaths within the basin from source springs to terminal playa lakes based on hydrochemical facies. Evans (2005) and Minckley and Cole (1968) find spring discharge temperatures ranging from 23.7 °C to 34.7 °C and total dissolved solids range from approximately 900 to 1600 mg/L (source spring) to more than 300,000 mg/L (terminal playa lakes). Within the valley, spring water flows on the surface and through subsurface channels in karstified alluvium.

Chloride Balance Approach to Recharge Estimation

Chloride balance is an appropriate method to estimate recharge in semiarid regions with sparse hydrogeologic data (Dettinger 1989). It has been used to estimate ground water in the Great Basin of Nevada and in other arid and semiarid regions. Anderholm (2000) estimated mountain-front recharge in the Middle Rio Grande Basin of Central New Mexico at 0.7% to 15% of total annual precipitation (~360 mm/year). Wilkes et al. (2004) estimated recharge at approximately 7% of mean annual precipitation in a fractured and weathered granite porphyry aquifer overlain by a shallow sandy aquifer in the Augustus River catchment of Western Australia. Mahlknecht et al. (2004) determined in the Independence Basin of the Mexican Altiplano (6840 km^2) that recharge primarily occurs in mountainous highlands (greater than 800 mm/year or 100% of annual precipitation) and little recharge occurs in the plains (10 mm/year or ~2.50% of annual precipitation). There, precipitation ranges from more than 400 mm in the plains as low as 1850 m amsl to more than 800 mm in highlands up to 2850 m amsl (Mahlknecht et al. 2004).

Precipitation Estimation

Spatially distributed precipitation over the study area is estimated based on a 60-year valley floor precipitation record and high-elevation precipitation based on mountain vegetation. Catchments are delineated along the hypothesized regional flowpath. Applying a chloride mass balance, the recharge for each successive basin is summed until recharge is equal to observed discharge.

Lesser y Asociados (2001) and Rodriguez et al. (2005) postulate that precipitation on the mountains surrounding CCB (i.e., Sierra San Marcos, Sierra La Fragua, Sierra La Madera, Sierra La Purísima, Sierra Vicente, and Sierra La Menchaca; Figure 2) can provide all ground water to basin springs. The goal of this recharge evaluation was to test if sufficient precipitation falls on the mountains immediately surrounding CCB (that Lesser y Asociados [2001] and Rodriguez et al. [2005] hypothesize to be CCB spring recharge zones) to generate measured spring discharge. The water budget is as follows:

$$\begin{aligned}\text{Recharge} &= (\text{Precipitation} - \text{Evaporative losses}) \\ &= \text{Canal discharge} + \text{Interbasin flow} \qquad (2)\end{aligned}$$

The accurate quantification of spatially distributed rainfall is essential to estimate ground water recharge. Precipitation is linearly extrapolated using a long-term precipitation record from the floor of CCB and by estimating precipitation at higher elevations based on the precipitation requirements of mountain vegetation. Figure 5 shows the three ground water catchments (red lines) delineated using methods described previously that are similar in area to those presented by Lesser y Asociados (2001) and Rodriguez et al. (2005). Precipitation in the catchments is hypothesized by Lesser y Asociados (2001) and Rodriguez et al. (2005) to provide recharge to CCB spring flow. We test the hypothesis of these authors that no interbasin flow to CCB occurs. The three ground water catchments are as follows: (1) the Ocampo Valley (6650 km^2) to the north that fed a spring-fed stream that historically flowed at approximately 0.25 m^3/s into the northern end of CCB (Minckley 1969); (2) the Sierra San Marcos and Sierra La Purísima (1450 km^2) are hypothesized to provide recharge to the Santa Tecla Canal that drains the eastern CCB; and (3) the Sierra La Fragua and southern Sierra La Madera (2450 km^2) are hypothesized to provide recharge to the Saca Salada Canal, which collects spring discharge on the western side of CCB.

Precipitation: Remotely Sensed vs. Sparse Gauge Measurements

Commonly, precipitation records are limited in many semiarid karstic aquifers around the world and CCB is no exception. To provide accurate precipitation estimates in areas of the globe where precipitation gauges are not present, Sorooshian et al. (2000) created the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks. This method estimates precipitation at a spatial resolution of 0.25° × 0.25° every half hour using satellite-based measurements for the past 6 years. Although satellite-derived precipitation estimates are a promising means to quantify precipitation where gauges are not available, a 6-year precipitation record is not sufficient to make accurate estimates of long-term average annual precipitation. Thus, we synthesize long-term, low-elevation gauge measurements with the precipitation requirements of mapped mountain vegetation to estimate precipitation at all elevations throughout the study area.

Rodriguez et al. (2005) present precipitation data measured in the town of Cuatrociénegas (at an elevation of 740 m amsl) from 1942 to 2003, with an average precipitation of 219 mm/year and a range between 100 and 400 mm/year. Precipitation falls primarily during heavy summer rains from May to October. September is the rainiest month (41.3 mm) and March is the driest months (5.5 mm; Rodriguez et al. 2005). The wettest year on

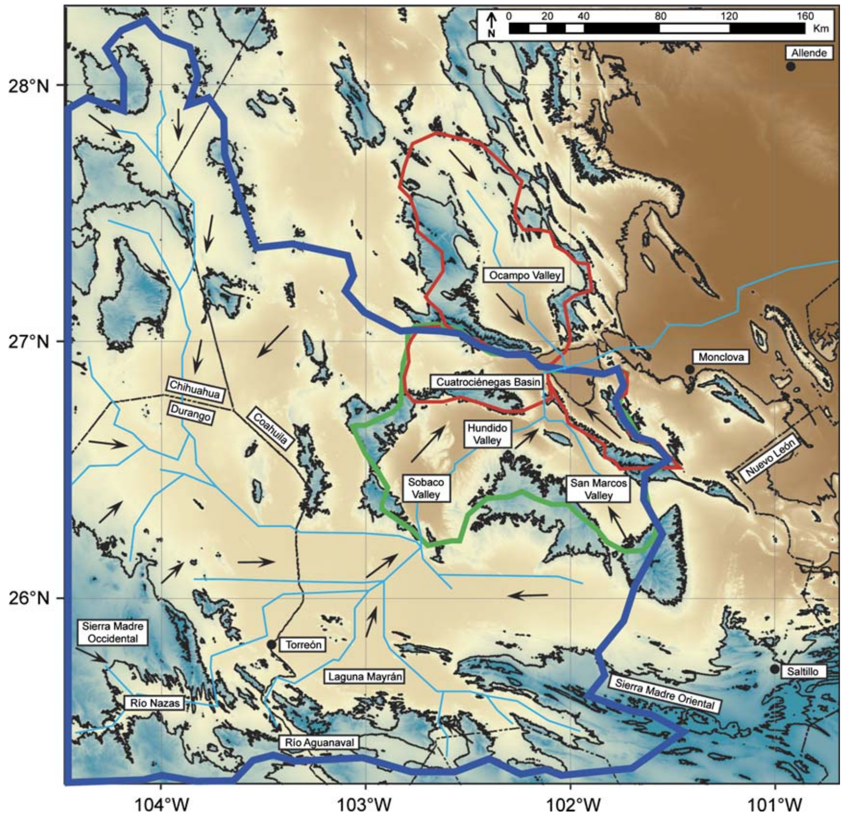

Figure 5. CCB ground water catchments. These include local flow systems of Saca Salada and Santa Tecla Canals and Ocampo Valley (thick red lines); expanded flow system including Sobaco, Hundido, and San Marcos Valleys (thick green line); approximately 91,000 km^2 regional flow system (thick blue line); hypothesized regional ground water flow system (black arrows) inferred surface drainage network (light blue line); and 750-m contour intervals (low- to high-elevation ranges from brown to green, respectively).

record is 1985 (421 mm). Rodriguez et al. (2005) also state that a station in the Hundido Valley yields a 14-year average precipitation (1991 to 2004) of 137 mm/year. Table 5 presents a summary of published CCB area precipitation estimates.

Precipitation: Spatial Distribution Based on Vegetation Requirements

Spatially distributed precipitation estimates are improved by evaluating the precipitation requirements of vegetation that occurs in CCB region. This evaluation is based on a linear relationship between long-term gauge precipitation values and mountaintop vegetation precipitation requirements at a 90-m^2 spatial resolution in a GIS environment.

A vegetation map (Meyer 1973) delineates the extent of pine trees in the Sierra San Marcos and Sierra La Madera ranges surrounding CCB, which occur at approximately 2000 m amsl on the northern slopes of the Sierra de la Madera and Sierra San Marcos and approximately 2400 m amsl on the southern slope of the Sierra de la Madera. Kolb (2005) states that ponderosa pines in northern Arizona thrive when annual precipitation ranges between 450 and 650 mm/year. González (2006) comments that approximately 400 mm/year precipitation occurs in the highest mountains surrounding CCB in thin pine tree stands. Because the Sierra San Marcos peak is at 2600 m amsl and the Sierra La Madera tops out at 3025 m amsl, two extrapolations of precipitation estimate recharge spatially distributed for a continuous range of elevations from valley floors to mountaintops throughout the study area to account for uncertainties in actual spatially distributed precipitation.

Catchment Delineation

Digital elevation data (DEM) were downloaded from the U.S. Geological Survey Seamless Data Distribution System at a 3 arc-s spatial resolution (~90 m^2) for an area that encompasses CCB and extends from approximately 24.87° to 28.70° north latitude and 100.68° to 104.75° west longitude (Hall et al. 2005). This includes most of the state of Coahuila, the easternmost part of the state of Chihuahua, northeastern state of Durango (including the currently internally draining terminus of the Río Nazas and the eastern Sierra Madre Occidental), northern Zacatecas state, and western Nuevo León state (including the northernmost Sierra Madre Oriental). The DEMs were imported into a GIS to create a regional DEM, and a spline interpolation routine fills occasional null data points (Hall et al. 2005).

Tarboton (1997) and Maidment (2002) describe a method for the determination of surface water flow directions from DEMs. This approach is used to infer regional hydraulic gradient from high-elevation recharge areas to low-elevation discharge zones, as well as to

Table 5
Precipitation Estimates, CCB

Source	Precipitation (mm/year)	Elevation (m amsl)	Comments
Badino et al. (2004)	260	740[1]	Cuatrociénegas town
	350	1500–2000[2]	Sierra San Marcos
Meyer (1973)	<200	740[1]	Cuatrociénegas valley floor
Minckley and Cole (1968)	<200	740[1]	Vivó Escoto (1964)
Minckley (1969)	<200	740[1]	Cuatrociénegas valley floor
Rodriguez et al. (2005)	219	740	Cuatrociénegas town, 1942–2003
	137	800[2]	Hundido Valley, 1991–2004
Secretaria de Medio Ambiente y Recursos Naturales (2003)	<200	NA	Chihuahuan Desert precipitation (Shreve 1944)
González (2006)	~400	2600–3025[3]	Mountain precipitation

[1]Elevation for Cuatrociénegas not specifically stated.
[2]Approximate elevation.
[3]González (2006) comments that 400 mm/year precipitation occurs in the highest mountains surrounding CCB. The Sierra San Marcos peak is 2600 m amsl, and the the Sierra La Madera tops out at 3025 m amsl.
NA = not available.

delineate catchments based on surface topography (and associated ground water catchments, referred to as catchments). Recharge calculations are conducted for each surface water catchment.

Recharge Estimation by Chloride Balance

Spatially distributed recharge is estimated by (Anderholm 2000; Dettinger 1989):

$$R_{\mathrm{mf}} = P\,\mathrm{Cl}_p/\mathrm{Cl}_r \qquad (3)$$

where R_{mf} is volume of mountain-front recharge (or spring discharge), P is mountain precipitation volume, Cl_p is chloride concentration of bulk precipitation (mg/L; Lamb and Bowersox 2000), and Cl_r is chloride concentration of mountain-front recharge (i.e., chloride concentration of spring discharge, mg/L; Evans 2005; Rodriguez et al. 2005; Johannesson et al. 2004).

The method assumes that:

1. Precipitation represents the only chloride source (i.e., dry deposition of chloride is minimal).
2. No chloride sinks or changes in chloride storage occur within the system.
3. All ground water discharges to springs (i.e., no interbasin ground water outflow from CCB).
4. Spring chloride concentrations represent the average chloride concentration of mountain-front recharge.

Precipitation Chloride Concentration

Rodriguez et al. (2005) collected a rain water sample for stable isotope analyses, but chloride analyses were not conducted (Gallardo 2006). Evans (2005) used an average chloride content of precipitation of 0.13 mg/L (1980 to 2004) measured at the closest National Atmospheric Deposition Program station in Big Bend National Park (TX04), located approximately 300 km to the north (Lamb and Bowersox 2000). Due to uncertainties in actual precipitation chloride, a value of 2.0 mg/L (Drever 1997, using data presented by Junge and Werby 1958) was also used to assess recharge resulting from a range of precipitation chloride concentrations.

Spring Water Chloride Concentration

Evans (2005), Rodriguez et al. (2005), and Johannesson et al. (2004) present chloride analyses for both source springs (i.e., first emergence of spring water from aquifer) and resurgent springs (i.e., springs located far from original source spring) samples (Figure 6). Only source springs are considered in the chloride balance analysis to avoid including evaporative effects on chloride concentrations. Andring et al. (2006) use plots of chloride and bromide to show that dissolution of halite does not influence CCB spring water chloride concentration (Figure 7). CCB springs feed two separate canals, Santa Tecla Canal, which drains springs in the east half of the basin, and Saca Salada Canal, which captures western basin spring discharge. The chloride concentrations of these two groups of springs are different. Therefore, we group them accordingly (Tables 6 and 7).

For estimating recharge in the Ocampo Valley that formerly supplied the spring-fed Río Cañon, Saca Salada Canal chloride values are used.

Spring Discharge Measurement

Instantaneous spring discharge measurements were conducted on the Saca Salada and Santa Tecla Canals using a FlowTracker® handheld acoustic Doppler velocimeter (ADV; Figures 2 and 8). Prior to ground water development in CCB, spring discharge flowed to an evaporative playa lake in the eastern part of the basin. Now, gauging these two canals estimates composite spring discharge (gauging dozens of individual springs is impractical). A water level pressure transducer is recording instantaneous stage in the Saca Salada Canal to estimate average annual basin discharge with a stage-discharge curve.

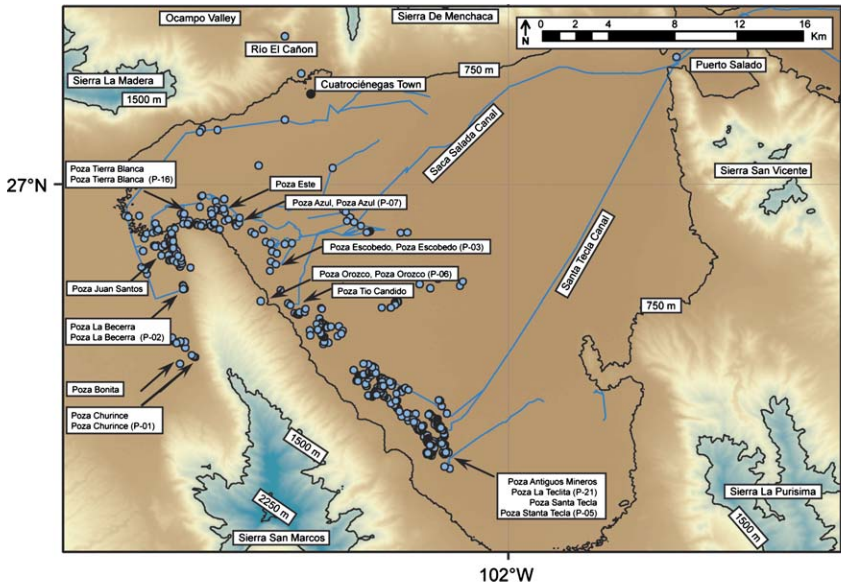

Figure 6. Location of CCB source springs. Tables 6 and 7 show results of chloride analyses for springs shown on this figure.

Evaluation of Interbasin Ground Water Flow with Analytical Model

The chloride balance recharge model tests if interbasin ground water flow must occur to generate observed springs discharge. An analytical model (Hermance 1998; Uliana 2000; Jacob 1943) evaluates if interbasin ground water flow from adjacent valley to CCB is possible under topographic divides by calculating hydraulic head given a range of plausible permeability and recharge conditions.

Interbasin Ground Water Flow in Analogous Karstic Terrains

Previous studies suggest that interbasin ground water flow occurs under topographic highs of high-permeability carbonate rocks in West Texas (Gates et al. 1980; Nielson and Sharp 1985; Sharp 1989, 1998; Darling 1997; Uliana 2000; Uliana and Sharp 2001; Hibbs and Darling 2005) and Nevada (Maxey and Eakin 1949; Snyder 1962; Eakin and Moore 1964; Eakin 1966; Maxey 1968; Eakin et al. 1976; Anning and Konieczki 2005; Winograd and Thordarson 1975). Snyder (1962) presents a hydrogeologic conceptual model of a closed and drained basin in the Great Basin of the western United States. Hibbs and Darling (2005) also suggest closed, drained basins occur in West Texas in alluvial basins underlain by highly permeable deep aquifers. Tóth (1963), Back (1966), and Freeze and Witherspoon (1967) show that regional ground water flow systems can exist underneath topographic highs.

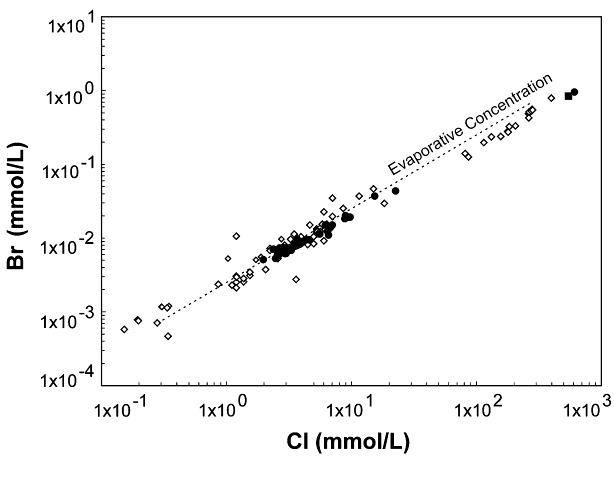

Figure 7. Bromide vs. chloride of water samples from wells (hollow diamonds) and springs (solid dots). The dashed line represents evaporative concentration, and the solid square shows a representative sea water value. If halite dissolution were occurring, the samples would show an enrichment of chloride relative to bromide as the water evolve; thus, we assume that chloride in spring water originates from precipitation.

Evaluation of Interbasin Ground Water Flow in CCB

The analytical model investigates the possibility of interbasin ground water flow into CCB from two adjacent basins as follows: (1) Ocampo Valley (to the north) and (2) the Hundido Valley (to the south-southwest; Figure 2). The model calculates whether or not a ground water divide is formed under (1) the Sierra La Madera and (2) the Sierra La Fragua, based upon ranges of recharge rates and hydraulic conductivity values. The systems consist of basin-fill valleys underlain by carbonate rocks and separated by carbonate rock topographic highs (Lesser y Asociados 2001).

The model calculates hydraulic head at any point (x) in an unconfined aquifer based on the boundary conditions of heads (h_1 and h_2) on either side of a topographic divide separated by length (L) comprised a porous material with a hydraulic conductivity (K). Hydraulic conductivity is calculated by dividing transmissivity by the average saturated aquifer thickness ($h_1 + h_2/2$). A constant recharge (W_s) is applied to the top of the topographic divide. The existence of a ground water divide under a topographic divide is evaluated with the

Table 6
Results of Chloride Analyses for Springs Feeding Santa Tecla Canal

Site[1]	Sample Date[2]	Chloride Concentration (mg/L)	Average Chloride Concentration (multisample)[3] (mg/L)	Source[4]
Poza Antiguos Mineros	Spring 2004	45.63	45.63	Evans (2005)
Poza Santa Tecla (P-05)	May 6, 2004	30.50	29.75	Rodriguez et al. (2005)
Poza Santa Tecla	1983	29.00		Johannesson et al. (2004)
Poza Escobedo	Spring 2004	102.40	100.30	Evans (2005)
Poza Escobedo	July 1983	107.00		Johannesson et al. (2004)
Poza Escobedo (P-03)	May 5, 2004	91.50		Rodriguez et al. (2005)
Poza La Teclita (P-21)	August 4, 2004	29.60	29.60	Rodriguez et al. (2005)
Poza Orozco (P-06)	May 6, 2004	91.50	91.50	Rodriguez et al. (2005)
Poza Tío Cándido	July 1983	119.00	107.46	Johannesson et al. (2004)
Poza Tío Cándido	Spring 2004	95.91		Evans (2005)
Approximate average			67.37[5]	

[1]Sample name in parenthesis is Rodriguez et al. (2005) nomenclature.
[2]Samples collected by Evans (2005) for Spring 2004 do not have a specific sample date.
[3]Average chloride concentration is not flow weighted because discharge measurements are not available for all springs. Poza Orozco and Poza Tío Cándido are located in the Santa Tecla (eastern CCB) drainage area but actually drain to the Saca Salada canal. Because discharge is relatively low, these springs are accounted for in the Santa Tecla Canal calculations.
[4]Johannesson et al. (2004) report results of analyses conducted on samples collected by Winsborough (1990) in 1983.
[5]Multisample average is used for chloride balance calculations.

analytical model by varying recharge as a percentage of precipitation on the topographic divide to consider a range of permeability and recharge scenarios. When the calculated head at $x = 1$ m is greater than h_1, a ground water divide exists. When the calculated head at $x = 1$ m is less than h_1, ground water flows downgradient and interbasin ground water flow occurs. The equation for the analytical model is as follows:

$$h(x) = \sqrt{h_1^2 + \frac{(h_2^2 - h_1^2)}{L}x + \frac{W_s}{K}\left(\frac{L}{2}\right)^2 - \frac{W_s}{K}\left(x - \frac{L}{2}\right)^2} \tag{4}$$

Head values were assigned for the model boundary conditions using land surface elevation as a proxy for predevelopment ground water level, assuming (1) predevelopment phreatic playas represent ground water levels in the Ocampo and Hundido Valleys and (2) spring elevations represent ground water elevation in CCB. Land surface and spring elevations were derived from a regional 90 m^2 DEM (Hall et al. 2005).

Two analyses based on the model input parameters presented in Table 8 were conducted (lines shown on Figure 2). Line 1 extends 4 km from the location of a predevelopment phreatic playa at the southern end of the Ocampo Valley to Poza Anteojo in the northern end of

Table 7
Results of Chloride Analyses for Springs Feeding Saca Salada Canal

Site[1]	Sample Date[2]	Chloride Concentration Sample (mg/L)	Chloride Concentration of Multisample Average[3] (mg/L)	Source[4]
Poza Azul	Spring 2004	59.98	75.74	Evans (2005)
Poza Azul (P-07)	May 6, 2004	91.50		Rodriguez et al. (2005)
Poza Becera	Spring 2004	101.20	98.90	Evans (2005)
Poza Becera	July 1983	104.00		Johannesson et al. (2004)
Poza Becera (P-02)	May 4, 2004	91.50		Rodriguez et al. (2005)
Poza Bonita	Spring 2004	106.40	107.20	Evans (2005)
Poza Bonita	July 1983	108.00		Johannesson et al. (2004)
Poza Churince	January 2005	103.55	103.95	Evans (2005)
Poza Churince	Spring 2004	104.80		Evans (2005)
Poza Churince (P-01)	April 30, 2004	103.50		Rodriguez et al. (2005)
Poza Este	Spring 2004	87.81	87.81	Evans (2005)
Poza Juan Santos	Spring 2004	105.30	98.84	Evans (2005)
Poza Juan Santos	Spring 2004	92.37		Evans (2005)
Poza Tierra Blanca	Spring 2004	114.70	107.85	Evans (2005)
Poza Tierra Blanca (P-16)	July 29, 2004	101.00		Rodriguez et al. (2005)
Approximate average			98.75[5]	

Note: See Table 6 for explanation of notes.

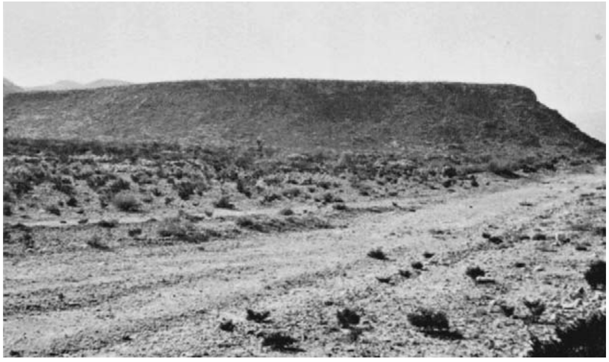

Figure 8. Possible lacustrine travertine deposit. Photo by Minckley (1969).

CCB. Line 2 extends 21 km from the location of a vadose playa (that was probably phreatic prior to water resource development, given the nearby seep described by Rodriguez 2005) at the northern end of the Hundido Valley to CCB. The second elevation on line 2 was selected at Poza El Churince.

Results and Discussion

The results of (1) precipitation estimation; (2) delineation of ground water catchments; (3) measurement of spring discharge in canals; (4) estimation recharge using a chloride mass balance approach; (5) evaluation of inter-basin ground water flow using an analytical model; and (6) evaluation of the regional flow system supplying CCB springs are discussed.

Precipitation Estimation

This section presents the results of spatially distributed precipitation in the CCB regional study area used to calculate recharge with the chloride balance method.

Linear Precipitation Extrapolation

Precipitation is extrapolated linearly for two different precipitation–elevation relationships. González (2006) specifies a maximum precipitation of 400 mm/year on the highest mountains but not a specific elevation or mountain range. Thus, precipitation is linearly extrapolated based on the maximum elevation of two CCB area mountain ranges (Sierra San Marcos, 3025 m amls, and Sierra La Madera, 2600 m amls) to generate spatially distributed precipitation estimates for the study area defined by the following equations:

Sierra San Marcos (3025 m amls):

$$\text{Precipitation}(\text{m/year}) = 0.000097(\text{Elevation, m}) + 0.146989 \quad (5)$$

Sierra La Madera (2600 m amls):

$$\text{Precipitation}(\text{m/year}) = 0.000079(\text{Elevation, m}) + 0.160383 \quad (6)$$

Both extrapolation equations are used for estimating spatially distributed recharge throughout the study area. We use two precipitation extrapolation equations to give a range that accounts for uncertainty in spatially distributed precipitation values.

Catchment Delineation

A total of 56 catchments in or upgradient to CCB with areas of 58 to 5153 km^2 in addition to a regional surface water drainage network were generated in GIS based upon surface topography for the study area (Figure 5). The most interesting finding of the catchment delineation is that a large surface water catchment (~91,000 km^2) exists upgradient of CCB. Previous studies (Lesser y Asociados 2001; Rodriguez et al. 2005) assert that only catchments totaling approximately 3030 km^2 provide flow to CCB. However, Echelle and Echelle (1998) use fish fauna to assert a hydraulic connection existed between the Río Nazas (which drains the Sierra Madre Occidental at the southwest corner of the study area), CCB, and the Río Grande (via the Río Salado) and that an extensive lake system existed in the Chihuahuan Desert (including Laguna Mayrán) until the late Holocene, when either regional climatic drying or uplift in the eastern Sierra Madre Oriental severed the connection.

A surface hydraulic connection does not currently exist. However, it is possible that even as northeastern Mexico dried climatically in the late Holocene to the present day (Castiglia and Fawcett 2006), a regional ground water flow system persisted in the subsurface in highly permeable carbonate rocks. Evidence supporting this hypothesis includes (1) lacustrine travertine deposits; (2) lacustrine deltaic deposits; (3) deep canyons at CCB outlet (that were dry prior to canal development in the 1900s); and (4) large carbonate springs with relatively constant discharge.

Minckley (1969) suggests a travertine deposit ^{14}C dated by Rodriguez et al. (2005) at 17,000 years old that rises 30 to 40 m above the southwestern valley floor may be evidence of a former lake filling CCB (Figure 8). Flat-topped, raised alluvial fans on the eastern flank of the Sierra San Marcos below two large canyons suggest lacustrine alluvial fan/deltaic deposition during a previous

Table 8
Analytical Model Input Parameters

Model Variable	Ocampo Valley to CCB (Line 1)	Hundido Valley to CCB (Line 2)
h_1 (m)	800	790
h_2 (m)	730	770
Δh (m)	70	20
b (m)	35	10
L (m)	4000	21,000
P, precipitation (mm/year)[1]	230	220
W_s, recharge[2]	Variable	Variable

[1]Precipitation presented in Rodriguez et al. (2005).
[2]Recharge (W_s) is considered as a percentage of precipitation and is varied from 0.00001% to 100,000% of precipitation to consider a range of precipitation and recharge scenarios.

wetter climate when CCB was filled by a lake. Present surface drainage from the canyons bypasses the raised fans, downcutting channels behind the older alluvial deposit. While no beach deposits have been noted in CCB, the ancestral Lake Sacramento of New Mexico did not leave beach deposits in a similar karstic terrain (Hawley 1993).

Deep canyons exist in the north-south trending ridges that form the eastern boundary of CCB. While the basin was formerly closed, surface water flowing in a previous wetter period most certainly carved these features (Figure 9). Downcutting of the ridges on the eastern border of CCB drained the lake that filled CCB, stranding a travertine deposit and alluvial fans. A canyon also exists where the Río Canyon used to drain the Ocampo Valley, suggesting significant discharge in past wetter climates.

While surface water discharge does not currently occur in this 91,000 km^2 catchment upgradient to CCB (other than water from the Río Nazas, which is entirely used for irrigated agriculture in the vicinity of the city of Torreón), we infer that this large catchment represents the possible extent of a regional carbonate aquifer providing constant discharge to CCB.

Spring Discharge Measurement

Spring discharge measurements (conducted using a handheld ADV) in the two canals draining CCB are presented in Table 9 (see Figure 2 for measurement locations).

Saca Salada canal discharge fluctuates seasonally. During summer and fall, irrigation and increased evapotranspiration of riparian vegetation along the unlined canal reduce Saca Salada discharge. Conversely, Santa Tecla Canal discharge has steadily decreased during the study period during which time the region has experienced a prolonged drought. Thus, decreased Santa Tecla Canal discharge may represent the effects of a combined local and regional ground water flow system influenced by decreased Sierra San Marcos precipitation.

In addition to canal discharge measurements near CCB outlet, Poza La Becerra (CCB's largest spring) was gauged (Table 10).

Figure 9. CCB outlet canyon suggests erosion in past wetter climate. Unpublished photo by Miller (1961). Stream is fed by CCB canal discharge. Prior to canal construction in the early and mid-1960s, all CCB spring surface water discharge flowed to large playa lakes and wetlands in the southeast of the basin and surface water flow through this basin outlet canyon did not occur.

Table 9
Saca Salada and Santa Tecla Canal Instantaneous Discharge

Date	Saca Tecla Discharge (L/s)	Saca Salada Discharge (L/s)
January 29, 2005	216	1243
March 14, 2005	232	1321
October 29, 2005	170	934
January 9, 2006	176	1259
March 13, 2006	171	1258
June 11, 2006	159	885
Average	187	1150
Standard deviation	29	188

Note: Refer to location number 1 (Saca Salada Canal) and 2 (Santa Tecla Canal) in Figure 2 for canal gauging locations.

Measurements at Poza La Becerra show constant spring discharge from winter to summer 2006, supporting the hypothesis that a regional ground water flow system supports some springs in CCB.

In addition to instantaneous discharge measurements, long-term continuous pressure transducer data measuring canal stage were collected in the Saca Salada Canal from January 29, 2005, to July 11, 2006. Combined with the instantaneous discharge data, a stage-discharge relationship was constructed for the Saca Salada Canal. The stage-discharge curve has the following mathematical relationship:

$$\text{Discharge}(\text{L/s}) = (\text{Stage, m})(0.0009) + 0.891 \qquad (7)$$

The equation is used to calculate an average Saca Salada Canal discharge of approximately 930 L/s. Annual CCB spring discharge may be approximated by total canal discharge (Table 11).

Canal discharge measurements indicate an annual CCB spring discharge of approximately 3.5×10^7 m^3/year compared with an approximate canal discharge of approximately 5.3×10^7 m^3/year presented by Lesser y Asociados (2001). Due to a Saca Salada Canal transducer failure, actual canal discharge measurement may be closer to those of Lesser y Asociados (2001). However, the more conservative value is used for this study. Agricultural diversions and increased summer evapotranspiration decrease Saca Salada discharge. Actual composite

Table 10
Poza La Becerra Instantaneous Discharge

Date	Discharge (L/s)
January 3, 2006	548
March 17, 2006	592
June 11, 2006	594
Average	578
Standard deviation	26

Note: Refer to location number 3 in Figure 2 for canal gauging location.

annual spring discharge may be higher, supported by the consistent discharge measured at Poza La Becerra.

For the purposes of the recharge analysis, we consider historical inflow from the Ocampo Valley (Table 12). We ignore CCB ground water discharge, making this an even more conservative recharge analysis. If there is an interbasin ground water discharge from CCB to the east, this would further support the regional flow hypothesis.

Recharge Estimation with Chloride Balance Approach

This section discusses the results of the chloride balance recharge estimates on ground water catchments immediately surrounding CCB and in the larger regional ground water catchment (Table 13). Due to uncertainties in data, ranges of spatially distributed precipitation (*P*), spring discharge chloride concentration (Cl_r), and precipitation chloride concentration values (Cl_p) are considered for the chloride balance recharge analysis.

Figure 10 summarizes the results of the chloride balance recharge analysis for four cases. A local recharge area of approximately 4000 km^2 (Saca Salada and Santa Tecla catchments, CCB) produces observed spring discharge with high Cl_p and low *P*. A combined local and interbasin recharge area of approximately 7000 km^2 (CCB and the Hundido Valley) produces observed spring discharge with high Cl_p and high *P*. When low Cl_p and low *P* are considered, a regional interbasin recharge area of approximately 65,000 km^2 produces observed spring discharge. A regional interbasin recharge area of approximately 91,000 km^2 (including all catchments upgradient of CCB to the Sierra Madre Occidental and Sierra Madre Oriental and the Ocampo Valley to the north) produces observed spring discharge when low Cl_p and high *P* are considered.

Thus, for springs that feed the Saca Salada Canal, precipitation on local ground water catchments on the Sierra La Madera, Sierra La Fragua, and western flank of the Sierra San Marcos is not sufficient to generate observed discharge, which is estimated conservatively low.

If conservatively low precipitation chloride values are used, the water budget balances for an approximately 91,000 km^2 recharge area that stretches to the Sierra Madre Oriental and Occidental, as shown in Figure 5. This result suggests a large, regional aquifer system is providing water to CCB springs.

If a value of 2.0 mg/L precipitation chloride calculation is applied to a regional recharge area, calculated discharge is about an order of magnitude too large. Alternatively, springs in CCB may derive ground water from a regional carbonate aquifer system that was recharged in a past pluvial period of wetter climatic conditions.

When a regional ground water catchment is considered that includes CCB, in addition to the Hundido, Sobaco, and San Marcos Valleys, recharge estimates are in the middle of the four estimates (Figure 5), suggesting that ground water supplying CCB springs is recharged in ground water catchments located in the intermontane valleys 50 to 100 km to the south of CCB.

Evaluation of Interbasin Ground Water Flow Using an Analytical Model

Chloride balance recharge estimates suggest that a regional ground water system supplies CCB springs. The results of the analytical model suggest that interbasin flow is possible from the Ocampo and Hundido Valleys to CCB under regional precipitation values and plausible permeability values for carbonate terrains (Figure 11).

Interbasin flow occurs to the right of the line, and a ground water divide with an associated local flow system would form on the left of the line. Based on the analytical model, interbasin flow occurs from Hundido and Ocampo Valleys to CCB under plausible transmissivity and recharge conditions. The model considered recharge

Table 11
CCB Annual Canal Discharge

Canal	Discharge (m^3/year)
Saca Salada Canal	29,076,192
Santa Tecla Canal	5,897,232
Total annual CCB discharge	34,973,424

Table 12
CCB Flow Summary

Flow	Flow Rate (m^3/year)	Inflow/Outflow
Saca Salada Canal	29,000,000	Outflow
Santa Tecla Canal	6,000,000	Outflow
Ocampo Valley	8,000,000	Inflow[1]

[1]Prior to ground water development in the Ocampo Valley, the Río Cañon flowed into CCB.

Table 13
Range of Values for Percent of Precipitation Resulting in Recharge

Cl^- Precipitation (mg/L)[1]	Cl^- Springs (mg/L)[1]	% Precipitation Resulting in Recharge
Sierra San Marcos precipitation and Santa Tecla Canal springs[1]		
0.13[2]	67.67	0.19
2.00[2]	67.67	2.99
Sierra La Madera precipitation and Saca Salada Canal springs[3]		
0.13	98.75	0.13
2.00	98.75	2.03

Note: A range of values is considered to account for data uncertainty in the recharge analysis.
[1]Case 1: precipitation extrapolation equation for the Sierra San Marcos (low *P*), and spring discharge chloride concentration for springs feeding the Santa Tecla Canal (low Cl_r).
[2]Precipitation chloride concentration ranges from 0.13 (low Cl_p) to 2.00 (high Cl_p) mg/L.
[3]Case 2: precipitation extrapolation equation for the Sierra La Madera (high *P*), and spring discharge chloride concentration for springs feeding the Saca Salada Canal (high Cl_r).

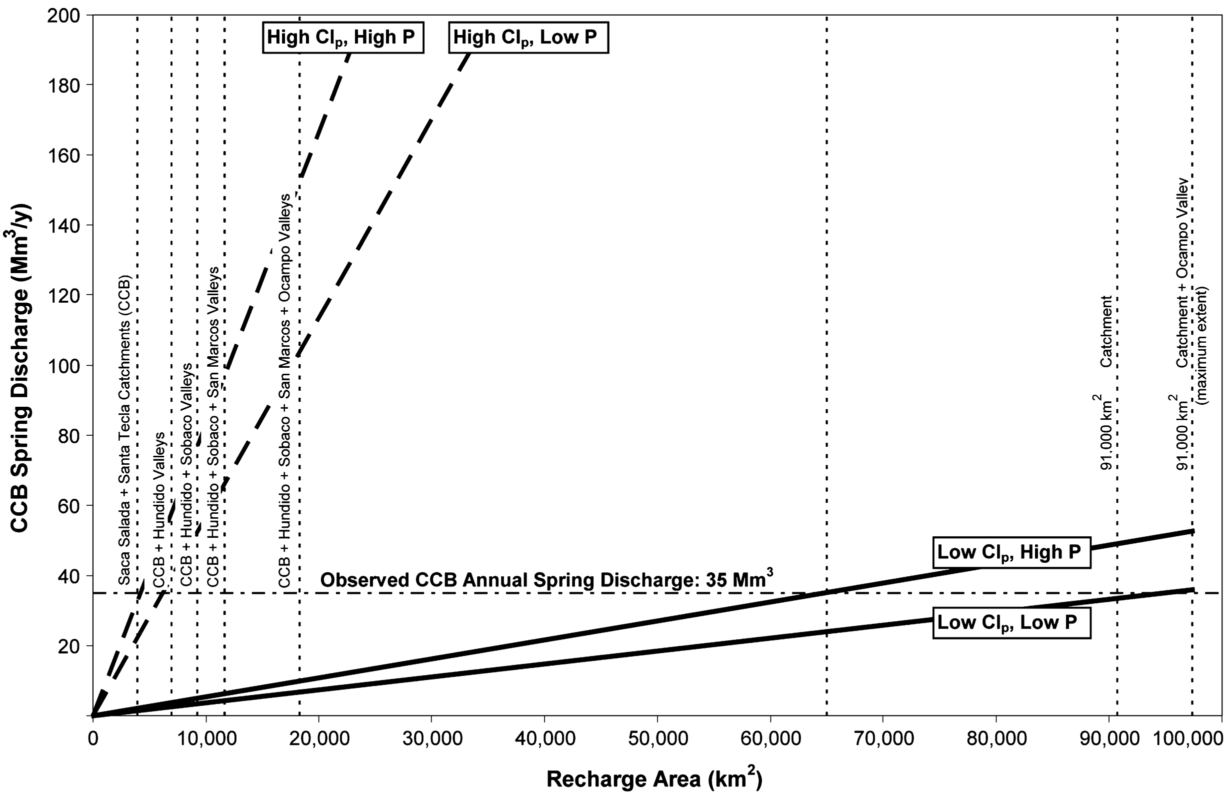

Figure 10. Recharge area vs. CCB spring discharge. A recharge analysis calculates the recharge area (km^2) needed to produced observed CCB annual spring discharge (35 Mm^3). Four cases (two bold dashed lines and two bold solid lines) account for data uncertainty: (1) high precipitation chloride concentration and high precipitation; (2) high precipitation chloride and low precipitation; (3) low precipitation chloride and high precipitation; and (4) low chloride and low precipitation. Horizontal dotted and dashed lines indicate the observed CCB annual spring discharge volume of 35 Mm^3. The eight dotted vertical lines show incrementally greater summations of plausible recharge catchments. A calculated discharge of 35 Mm^3 occurs when the bold solid and dashed lines intersect the dotted and dashed horizontal lines for the four different recharge scenarios. For reference, the 91,000 km^2 catchment corresponds to the thick blue line in Figure 5.

rates less than or equal to a 1% of precipitation (a typical recharge rate suggested by Gates et al. [1980] for arid West Texas) and typical carbonate rock transmissivity values. Local ground water flow systems would develop in the study area only under conditions of very high recharge rates that might have occurred during past pluvial periods or in isolated locations with lower than expected permeability values.

Ground Water Catchment Delineation: Local and Regional Flow Systems

During predevelopment conditions, a ground water–fed surface water system (and perhaps also associated interbasin ground water system) flowed from the Ocampo Valley to CCB (Figure 5). Local flow dominates in the Santa Tecla Canal spring system, with the majority of recharge originating in the Sierra San Marcos. However, some regional ground water flow probably contributes to these springs. In the springs that feed the Saca Salada Canal, high, steady discharge and higher chloride concentration dominate, suggesting a predominantly regional flow system that includes the Sobaco Valley, Hundido Valley, and San Marcos Valley. The Saca Salada Canal spring system may also include recharge from a larger regional aquifer system that may include recharge from the Río Nazas or mountains in eastern Chihuahua.

Conclusions

We develop an integrative data approach that provides a framework for the evaluation of recharge areas in developing arid karstic aquifer systems with sparse hydrogeologic data globally. In this research, we integrate disparate geologic data, including field observations; historical hydrologic data (that may be anecdotal); and all other available data, including geologic maps, DEMs, GIS, analytical models, water quality parameters, environmental isotopes, and spring discharge data, to evaluate recharge areas to support development of effective ground water management policies.

In northeast Mexico, long-term well records are sparse. Delineation of ground water catchments based upon surface topography and geology reveals an approximately 91,000 km^2 basin upgradient of CCB that includes the terminal drainage of the Río Nazas near the city of Torreón, which has headwaters in the Sierra Madre Occidental. A surface water flow system probably existed until the late Pleistocene that linked the Río Nazas to the Río Grande via a series of Chihuahuan Desert lakes, which included CCB (and Laguna Mayrán near the city of Torreón; Figure 1). As the regional climate dried, surface water drainages became truncated, but a regional aquifer exists, and interbasin ground water flow occurs under topographic divides between valleys (e.g., the Hundido and

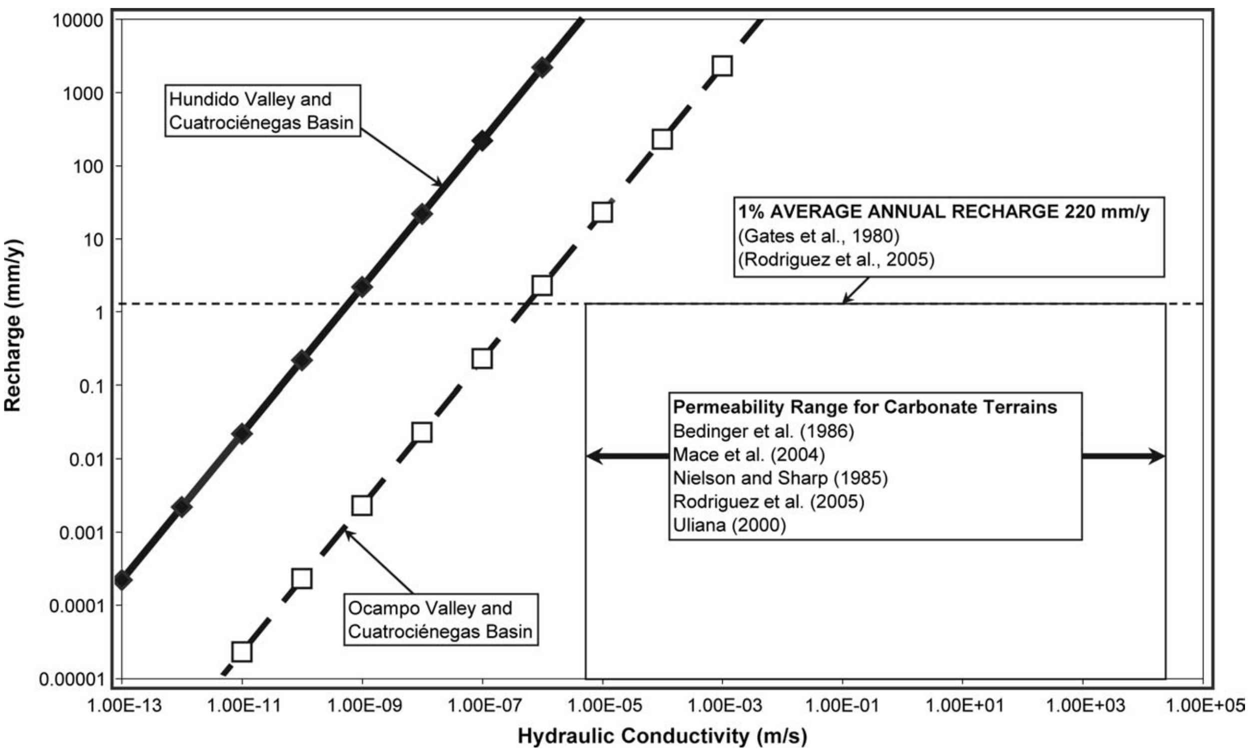

Figure 11. Results of analytical model evaluating interbasin ground water flow between the Ocampo and Hundido Valleys and the CCB. The analytical model shows that interbasin ground water flow occurs from adjacent valleys to the CCB under the 1% recharge dotted line and to the right of the two diagonal model solution lines in the shaded box of plausible permeability values.

Sobaco Valleys). Currently, CCB represents a low-elevation discharge zone of a regional aquifer system.

Regional flow provides ground water to large, nearly constant discharge springs in CCB (such as Poza La Becerra, Poza Azul, Poza Escobedo, and Poza Churince). A mixed local and regional ground water flow system supplies water to smaller springs at the head of the Santa Tecla Canal on the eastern flank of the Sierra San Marcos, which decrease discharge significantly during periods of drought. Recharge estimates in the Ocampo Valley appear to be sufficient to generate historical, predevelopment Río Canon discharge (neglecting interbasin ground water discharge).

Due to the uncertainty of chloride concentration in precipitation, it is unclear if the entire approximately 91,000 km^2 regional ground water catchment currently provides for basin spring flow. However, we infer that regional flow sustains the larger springs (such as Poza La Becerra, Poza Azul, Poza Escobedo, and Poza El Churince). Either a significant portion of ground water discharge is currently recharged in the intermontane basins within approximately 100 km to the south and west of CCB or ground water recharged during previous wetter climatic periods flows to CCB from a portion of a larger 91,000 km^2 regional carbonate aquifer. We infer that ground water currently flows from mountain highland recharge areas surrounding the Sobaco, Hundido, Ocampo, and San Marcos Valleys to CCB and may also include paleoground water recharged to the larger 91,000 km^2 regional aquifer system during past pluvial periods. The regional aquifer system follows a topographic gradient that during past pluvial periods may have linked the Río Nazas and the Río Aguanaval of the Sierra Madre Occidental to the Rio Grande via the CCB and other large, currently dry, upgradient lakes.

This study develops procedures to delineate regional ground water catchments in arid and semiarid karstic aquifers with sparse hydrogeologic data. The approach is tested in the CCB of northeastern Mexico, and the procedures may be used to understand the spatial extent and quantify recharge processes in similar terrains globally.

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