Transboundary Aquifers and Binational Ground Water Database for the City of El Paso / Ciudad Juarez Area

A Binational Publication
Principal Participants
United States of America
International Boundary and Water Commission (IBWC)
United States Environmental Protection Agency (USEPA)
Texas Water Development Board (TWDB)
New Mexico Water Resources Research Institute (NMWRRI)
Estados Unidos Mexicanos Comisión Internacional de Limites y Aguas (CILA)
Comisión Nacional del Agua (CNA)
Junta Municipal de Agua y Saneamiento de Ciudad Juárez (JMAS)
January, 1998

FORWARD

This document integrates official ground-water data from the United States and Mexico into one data base. These data were exchanged during a series of official meetings held in the offices of the Comisión Internacional de Limites y Aguas and the International Boundary and Water Commission, respectively in Ciudad Juárez, Chihuahua and El Paso, Texas.

In addition to the international ground-water data base, this document includes a general report that summarizes and integrates the data graphically, and prepares other hydrogeologic maps and figures from the published literature. The graphics and maps in the report are mostly limited to the data in the attendant ground-water data base. However, additional surface water and ground-water data that were derived from previously published sources are presented in a few figures. The earlier data have been officially approved and archived by the U.S. Geological Survey, the International Boundary and Water Commission, and the Comisión Nacional del Agua. By international agreement the format of this general report provides limited processing of ground-water data, but no discussion of the significance or ramifications of the data or figures. The reader is at liberty to derive independent conclusions from these data that do not reflect the official opinions, either expressed or implied, of the principal participants in the study.

PARTICIPATING AGENCIES

Participating United States agencies include the Texas Water Development Board (TWDB), the New Mexico Water Resources Research Institute (NMWRRI), the International Boundary and Water Commission (IBWC), and the United States Environmental Protection Agency (USEPA). Participating Mexican agencies include the Comisión Nacional del Agua (CNA), the Junta Municipal de Agua y Saneamiento (JMAS) de Ciudad Juárez, and the Comisión Internacional de Limites y Aguas, (CILA). Text was written by Barry Hibbs. Report assembly and cartography were by the TWDB.

LIST OF PRINCIPAL PARTICIPANTS FOR EACH AGENCY

COLLABORATORS

United States: Texas Water Development Board (Steve Moore, Ericka Boghici, Frank Bilberry, Jay Galvan, Steve Gifford, Mike McCathern, Miguel Pavon); New Mexico Water Resources Research Institute (Pamela Hann, Kenny Stevens); LBG-Guyton Associates (Bruce Darling); Texas Bureau of Economic Geology (Edward Collins, William Mullican); U.S. Geological Survey (Linda Beal, Mike Kernodle, Brennon Orr); El Paso Public Supply Board (Sayeed Joraat, Ernest Rebuck, Roger Sperka); University of Texas at El Paso (Nancy Lowery).

Mexico: Comisión Internacional de Limites y Aguas (Hector Orta); Comisión Nacional del Agua (Orlando García Rojas, Eric Morales Casique); Junta Municipal de Agua y Saneamiento (José M. Canizales, Ricardo Sánchez).

EXECUTIVE SUMMARY

This binational aquifer study and data report was published under a cooperative agreement between the participating agencies in the United States and Mexico. Binational data that are archived in this document include information on land use, well data, core descriptions, ground-water levels in wells, ground-water quality analyses, and pumping records. General ground-water data and characteristics of the Hueco-Tularosa aquifer, southeastern Hueco aquifer, and Rio Grande aquifer below the El Paso narrows are presented in the narrative of the report. Study results for each aquifer are as follows:

Hueco-Tularosa Aquifer

A surface divide near the New Mexico/Texas State line separates the Tularosa Basin (a closed basin) and the Hueco Basin (a through-flowing basin) topographically. The surface divide does not correspond to a structural or ground-water divide, and the two basins are connected by interbasin ground-water flow from New Mexico into Texas. Because of the interconnection, the Tularosa and Hueco Basins are considered in this report as one aquifer; the Hueco-Tularosa aquifer. For convenience, the Hueco-Tularosa aquifer is designated to include water bearing strata in both the flanking highlands and saturated bolson fill.

Total surface area of the portion of the Hueco-Tularosa aquifer evaluated in this report is 10,800 km^2. Approximately 67% of its land area is in New Mexico and 22% of its land area is in Texas. About 11% of its land area is in Mexico. The aquifer is the key source of water for the City of El Paso and Ciudad Juárez, and for military installations and smaller cities in New Mexico, Texas, and Mexico.

Depth to ground water in the Hueco-Tularosa aquifer is variable. Depth to ground water near the Cities of Tularosa and Alamogordo at the flanks of the Sacramento Mountains is between 6 and 46 m. Drawdowns in many municipal wells, up to 30 m, have been recorded in this area. Ground water is at or near ground surface at Alkali Flat due to evaporative discharge from a wet gypsum playa. Depth to ground water near the White Sands Missile Range Headquarters, at interior portions of the basin, is up to 122 m. Little drawdown has been recorded there. Drawdowns in the Hueco Bolson near the New Mexico/Texas State line has been relatively small, not exceeding 9 m. Current depth to ground water beneath the City of El Paso is usually between 76 and 122 m at distances from the Rio Grande. Present depth to ground water beneath Ciudad Juárez varies from about 30 to 76 m, except near the Rio Grande where depths are often less than 20 m.

In heavily developed parts of the Hueco-Tularosa aquifer, drawdowns since 1940 are up to 45 m. Pumping cones of depression in municipal wellfields are the focal points of drawdown. Most of the drawdowns near municipal wellfields vary between 15 and 30 m. Focal points of drawdown are shown beneath El Paso and Ciudad Juárez.

Most ground-water discharge from the Hueco Bolson is due to pumping withdrawals for municipal and military water supply. Quantities of ground water pumped from the Hueco Bolson from municipal and other sources have increased by a factor of almost 6 since 1950. Recent trends indicate that municipal pumpage in Mexico increased about 12.5% between 1990 and 1994. Municipal and military pumpage in the United States decreased 24.0% during the same time interval. Pumping trends reflect the increased dependance on ground water in Mexico, and partial conversion from ground water to surface-water use in the United States.

Ground water north of the New Mexico/Texas State line is usually greater than 1,000 mg/L TDS except in mountains and along mountain fronts, where ground water is usually less than 1,000 mg/L TDS. Many samples along the interior of the basin at or just south of Alkali Flat have TDS greater than 10,000 mg/L. Near and extending across state line to the Rio Grande alluvium, ground waters along the Franklin Mountains are characteristically less than 700 mg/L TDS. Basinward of the recharge areas along the Franklin Mountains salinities increase to over 1,000 mg/L in many wells, reaching concentrations over 1,500 mg/L in wells along the axis of the basin. Salinities of ground water underlying the Ciudad Juárez area are generally less than 1,000 mg/L.

Chloride and other dissolved ions have increased over time in many of the municipal wells in El Paso and Ciudad Juárez. Hydrochemical plots show a pattern of salinization of wells that have had significant long-term drawdowns. Chloride now exceeds 250 mg/L in several of the wells in the area.

Southeastern Hueco Aquifer

The southeastern Hueco Bolson is separated geographically from the Hueco-Tularosa Bolson at the El Paso/Hudspeth County line. A southeast trending linear aquifer, the bolson extends for 88 km from the El Paso/Hudspeth County line to its southeastern limit at Indian Hot Springs. The bolson is bounded on the north by the Finlay, Malone, and Quitman Mountains and Diablo Plateau. The Sierra de San Ignacio, Sierra de El Almagorsa, Sierra de San Jose Del Prisco, Sierra de Las Vacas, and Sierra de Carrizalillo define its southern boundary. For convenience, the southeastern Hueco aquifer is designated to include water bearing strata in both the flanking highlands and plateaus and saturated bolson fill.

The thickness of the bolson fill of the southeastern Hueco aquifer decreases from as much as 2,600 m at the El Paso/Hudspeth county line to an infinitesimal thickness where the bolson thins out near Indian Hot Springs. Saturated bolson fill is principally the lower basin fill series. The lower basin fill is mostly lacustrine clay, bedded gypsum, and minor sand, silt, and clay from both alluvial fans and local fluvial deposits. The upper basin fill series, a second lithologic unit, is thin and contains little water east of the El Paso/Hudspeth County line. The upper basin fill deposits were formed in alluvial fan, fluvial, and lacustrine systems and are composed of sand and gravel and minor silt and clay.

North of the Rio Grande, the regional potentiometric surface map shows high hydraulic heads and ground-water divides along the Diablo Plateau, Finlay Mountains, and Quitman Mountains. Areas of high head in the mountains and plateaus define focal points of recharge in the southeastern Hueco aquifer. Hydraulic head gradients in the Cretaceous and other bedrock strata are as much as 0.07 along ground-water divides and are as little as 0.04 along mountains fronts. Hydraulic gradients in the bolson fill are about 0.008. South of the Rio Grande, the potentiometric surface slopes to the river from high topographic elevations along mountain fronts. Springs flow at high elevations from the mountains in Mexico. These probably discharge from locally perched flow systems that do not define hydraulic head in the zone of regional saturation. Data are not adequate to define regional hydraulic heads beneath these mountains. Hydraulic gradients south of the Rio Grande, from mountain fronts to the river, are about 0.01 to 0.03.

The southeastern Hueco aquifer can almost be considered undeveloped, especially north of the Rio Grande. Low capacity domestic and livestock wells are used to satisfy the needs of the local population and livestock industry. This is partly a function of the low yield and relatively high salinities of the aquifer.

Total dissolved solids in the southeastern Hueco aquifer are typically greater than 1,000 mg/L in the mountains, increasing to as much as 4,000 mg/L in the bolson. The hydrochemical facies of southeastern Hueco aquifer ground waters on the United States side of the study area varies from Ca-Mg-HCO3 and Na-SO4 along the Diablo Plateau to Na-SO4-Cl beneath the floor of the basin. In Mexico, waters vary from Ca-Mg-HCO3 beneath the Sierra de San Ignacio, Sierra de El Almagorsa, and the Sierra de San Jose Del Prisco to Ca-Mg-SO4-Cl waters beneath the basin floor. Typically these ground waters have TDS that vary between 1,000 and 3,500 mg/L. Indian Hot Springs is an exception; Na-Cl water with TDS higher than 7,000 mg/L discharges from Cretaceous carbonate and clastic rocks at the hot springs.

Rio Grande Aquifer

Southeast of the El Paso narrows, the Rio Grande flows across a broad alluvial floodplain that has incised the surface of the Hueco Bolson. The Rio Grande alluvial floodplain in the El Paso/Juárez Valley is underlain by a complex mosaic of braided and meandering river deposits. Formed during alternating periods of scour and fill in the late Quaternary Period, the river deposits consist of irregularly distributed gravels, sands, clay, and silt lenses and beds. Alluvial fill consists of reworked bolson fill material, eroded bedrock, and extrabasinal sediments transported by the Rio Grande from its headwaters in New Mexico and Colorado to the El Paso/Juárez Valley.

Recharge to the Rio Grande aquifer along irrigated reaches is due primarily to infiltration of surface water that has been applied to irrigable crops. Recharge also occurs to some extent by direct seepage from diversion canals and river channels, although lining of the Rio Grande channel along the Chamizal zone limits recharge by the river locally. Other sources of recharge to the Rio Grande alluvium include direct precipitation on the floodplain surface, seepage from irrigation canals and drains, infiltration of runoff along arroyos, and recharge from cross-formational flow with the Hueco Bolson. Quantification of the amounts and spatial variability of recharge to the alluvial aquifer is infeasible with available data.

Ground water is discharged from the Rio Grande alluvium by irrigation pumping, by subsurface seepage to the Rio Grande, by leakage to drains, and by cross-formational leakage to the Hueco Bolson. Along the heavily urbanized Chamizal zone, discharge occurs primarily by cross-formational leakage from the alluvium to the Hueco Bolson where storage in the Rio Grande aquifer is depleted by heavy municipal pumping in the bolson aquifer. From Chamizal zone to the El Paso/Hudspeth County line, discharge occurs by irrigation pumping and by leakage to the many drains which help to maintain nearly constant water-levels in the alluvial aquifer. From the county line to Fort Quitman, discharge occurs by irrigation pumping, by seepage to the Rio Grande, and by leakage to a few drains.

Stiff diagrams indicate sodium-sulfate type ground-waters in the Rio Grande aquifer in El Paso County. Below the El Paso/Hudspeth County line, chloride increasingly becomes the dominant anion in the cation/anion pairing. Mexican ground waters follow the same general trend, but show greater scatter in the segment of the floodplain across from Hudspeth County. Ground-water samples frequently were collected in and beneath arroyo deposits that overlie earlier alluvial floodplain deposits in Mexico. Arroyos act as recharge areas after episodic precipitation events and ground-water chemistries have wide scatter due to commingling of dilute runoff waters and older alluvial ground waters.

Total dissolved solids in the Rio Grande aquifer in El Paso County vary substantially, but fall mostly within the 1,000 to 3,000 mg/L range. Total dissolved solids are higher in alluvial deposits in Hudspeth County, falling mostly within the 3,000 to 6,000 mg/L range. In both regions, total dissolved solids are lower in the Mexican part of the floodplain aquifer due to mixing of dilute runoff waters with older, higher salinity waters. This is an artifact of well locations closer to arroyos on the floodplain in Mexico.

Historical monthly water quality and streamflow data show changes in river water quality and discharge between El Paso/Ciudad Juárez and Fort Quitman. Spatial changes in sodium, sulfate, chloride, and total dissolved solids for most months indicate appreciable decline in river water quality downstream. Data indicate that water quality improves when river discharge is high during the irrigation season.

INTRODUCTION

The challenges of managing scarce ground-water resources along the El Paso/Ciudad Juárez corridor demands a complete understanding of the transboundary resources of the Hueco-Tularosa aquifer, southeastern Hueco aquifer, and Rio Grande aquifer. Forecasts predict the depletion of the recoverable freshwater reserves of these binationally shared aquifers by the middle half of the 21st century. Several strategies, including desalinization technologies, subsurface wastewater injection, aquifer storage and recovery, and conjunctive surface and ground-water use may extend the depletion forecasts. Imperative is the cooperation of the United States and Mexico to use the ground water resources of the aquifer wisely for the benefit of the citizens of both nations. This binational data library and technical report is an important and positive cooperative step.

Previous Work

Dating to Schlicter's (1905) study, several studies of ground-water resources in the El Paso/Ciudad Juárez area have been completed. In the United States, most studies have been limited to the area north of the international border in El Paso County. A few of the studies conducted in the United States have extended across the International border to include the Ciudad Juárez area locally (Meyer, 1976; Lee Wilson and Associates 1986; IBWC, 1989). Mexican water agencies and consultants have conducted a number of ground-water and geophysical studies in the Juárez Valley and in the immediate area of Ciudad Juárez (e.g., de la O'Carreno, 1957, 1958; Garcia, 1967; Geo Fimex, 1970; C.I.E.P.S., S.C., 1970).

Study Area

The aquifers evaluated in this report include the Hueco-Tularosa aquifer, the southeastern Hueco aquifer, and the Rio Grande aquifer between the El Paso narrows and Indian Hot Springs, Texas (Figure 1). The study area includes parts of Otero and Dona Ana Counties, New Mexico; part of Hudspeth County, Texas; all of El Paso County, Texas, and a smaller part of northern Chihuahua, Mexico. The study area includes the heavily developed portion of the Hueco-Tularosa aquifer beneath the City of El Paso and Ciudad Juárez.

Types of Ground-Water Information Exchanged

The ground-water databases included in this report have been provided by the participating agencies. The general types of data exchanged are: land use, well data (construction, ownership, well use, etc.), core descriptions, ground-water levels in wells, results of ground-water quality analyses, and pumping records. The information is organized by country and, in the case of the U.S., by state. Not all data types listed above are available for each entity. The data pertinent to the U.S. can be found in the folder U.S.A. which contains two sub-folders: *Texas and New Mexico*. Similarly, the Mexican data is located in the folder *Mexico. All the available information has been tabulated and saved in MS Excel 7.0* workbooks. Each workbook consists of spreadsheets named for the type of data they contain. Sample tables with headers and rows of data are shown in the Appendix A, at the end of this report. Efforts have been made to organize the U.S. information in a consistent manner. The Mexican data was grouped together in one file but was not otherwise modified or organized. The Mexican data presented in this report represents data that has been officially sanctioned for international distribution by the Federal Government of Mexico.

HUECO-TULAROSA AQUIFER

Location and Extent

The Tularosa Basin extends southward for 274 km from south-central New Mexico to a gentle surface divide about 11 km north of the New Mexico/Texas State line. The basin is bounded on the east by the Sacramento and Hueco Mountains and on the west by the San Andres, Organ, and Franklin Mountains. The Tularosa Basin is bounded on the north by Chupadera Mesa. Our study region terminates at the northern edge of Dona Ana and Otero Counties, New Mexico (Figure 2), which includes 6,700 km^2 of the basin's total surface area.

The surface divide near the New Mexico/Texas State line separates the Tularosa Basin (a closed basin) and the Hueco Basin (a through-flowing basin) topographically. The surface divide does not correspond to a structural or ground-water divide, and the two basins are connected by interbasin ground-water flow from New Mexico into Texas (Wilkins, 1986). Because of the interconnection, the Tularosa and Hueco Basins are considered in this report as one aquifer; the Hueco-Tularosa aquifer. For convenience, the Hueco-Tularosa aquifer is designated to include water bearing strata in both the flanking highlands and saturated bolson fill.

In Texas, the Hueco Bolson extends south from the New Mexico/Texas State line to the Sierra Juárez to the west and to the Sierra El Presidio and Sierra Guadalupe to the south. From the Sierra Juárez, the Hueco Bolson trends southeast to Indian Hot Springs. The part of the Hueco Bolson that extends southeast from the El Paso/Hudspeth County line to Indian Hot Springs is designated herein as the "southeastern Hueco Bolson." The separation is made partly for convenience and partly because of its different geographic orientation, low yield, and limited population. The southeastern Hueco Bolson and associated bedrock aquifers (collectively the southeastern Hueco aquifer) are discussed in the next section.

Total surface area of the portion of the Hueco-Tularosa aquifer evaluated in this report is 10,800 km^2. Approximately 67% of its land area is in New Mexico and 22% of its land area is in Texas. About 11% of its land area is in Mexico. The aquifer is the key source of water for the City of El Paso and Ciudad Juárez, and for military installations and smaller cities in New Mexico, Texas, and Mexico.

Basin Geometry and Rock and Sediment Types

The Tularosa and Hueco Bolsons are asymmetric grabens, bounded by mountains that are mostly tilted fault blocks. Faulting has produced steep escarpments on the east side of the San Andres and Franklin Mountains and moderately steep scarps on the west side of the Sacramento and Hueco Mountains. The trough of these grabens thicken generally from Alkali Flat to the New Mexico/Texas State line. Hydrogeologic cross sections show basin fill thickening and inferred geology at three transects across the basin (Figure 3). Major structural and stratigraphic boundaries in these maps (such as depth to bedrock) were prepared from surface geophysical data and testhole logs (Davis and Leggat, 1967; McLean, 1970; Geo Fimex, 1970).

Consolidated strata that provide small to moderate quantities of water in the highlands range in age from Precambrian to Tertiary. Most of the water wells in bedrock are shallow, and penetrate only a few tens of feet of saturated bedrock. The most prolific bedrock aquifers are karstified and fractured carbonate and clastic rocks. Intrusive and extrusive rocks and metamorphic rocks are not usually highly prolific.

Thick sequences of Paleozoic sedimentary rocks are exposed in the Sacramento Mountains. Precambrian granites, Precambrian metamorphic rocks, and Paleozoic sedimentary rocks are exposed in the San Andres Mountains. The northern Organ Mountains consist of masses of Tertiary intrusive rocks to the north, and Paleozoic, Cretaceous, and lower Tertiary sedimentary rocks to the south. The Franklin Mountains include sequences of Paleozoic carbonate rocks and Precambrian and Tertiary intrusive rocks. The Hueco Mountains are mostly carbonate and clastic rocks of Paleozoic and Cretaceous age. The part of the Diablo Plateau that bounds the Hueco and Tularosa Bolsons consists mostly of Permian and Cretaceous carbonate rocks and some Tertiary intrusive rocks. The Sierra Juárez, Sierra El Presidio, and Sierra Guadalupe of northern Chihuahua, Mexico are mostly carbonate and clastic rocks of Cretaceous age.

Basin fill sediments are usually weakly consolidated to non-consolidated, heterogeneous materials that overlie Precambrian through Tertiary rocks (Sandeen, 1954; de la O Carreno, 1957,1958; Geo Fimex, 1970; Wilkins, 1986). Non-indurated units in the Tularosa Bolson include gravels, sands, muds, and dune deposits; mostly gypsum sand. Weakly and moderately consolidated basin fill deposits include fanglomerates, conglomerates, soft sandstones, caliche, shale, and gypsum. Coarse materials are deposited on the flanks of the mountains and formed as alluvial fans.

Lower basin fill deposits in the Hueco Bolson include lacustrine muds, interbedded with layers of bentonitic claystone and siltstone and some discontinuous sand lenses. The upper basin fill is composed of mostly fluvial stream-channel and floodplain deposits. These and earlier deposits are juxtaposed against fanglomerates that flank the margin of the basin (Strain, 1966). Deposits in the upper basin fill are predominantly gravels and sands, interbedded with muds, volcanic ash, and caliche (Geo Fimex, 1970; Wilkins, 1986). Sand and gravel sediments in the upper basin fill are thickest along the Franklin and Organ Mountains and Sierra Juárez, becoming thinner and finer-textured along the axis of the basin (USBR, 1973). Throughout the basin, the percentage of clay increases generally with depth (Geo Fimex, 1970; Orr and Risser, 1992).

These same general trends are shown by the electrical resistivity cross section D - D' in Mexico (Figures 2 and 4). Vertical electrical soundings performed in the Hueco Bolson across from San Elizario (G1 to GVI) showed that aquifer resistivities are up to 100 ohm-m in the upper 50 to 200 meters of bolson fill (Figure 4). The high resistivity values suggest potable waters are present in relatively coarse-textured sediments. At depths between 250 and 500 meters, the electrical resistivity values are usually less than 15 ohm-m. Such low values imply clay-dominated strata, or strata saturated with slightly to moderately saline pore fluids (de la O Carreno, 1958; Dobrin, 1976; Kearey and Brooks, 1984). At depths greater than 600 to 750 meters, resistivity values are greater than 20 to 50 ohm-m, suggesting bedrock of probable Cretaceous age.

Southeast of GVI, (GVI to G6), electrical resistivities within the upper 200 meters of bolson fill are mostly less than 8 ohm-m, marking the transition from sand-dominated bolson deposits with potable waters, to clay-dominated bolson fill or coarse-basin fill saturated with inferior quality ground water (Figure 4). An exception is between G5A and D' where a 50 m thick layer of high resistivity material (100 ohm-m) is present. This thin layer probably represents coarse-textured bolson fill that may be associated with arroyo deposits formed along the Bandejas River Valley (Geo Fimex, 1970).

Current Water Levels

Near the cities of Tularosa and Alamogordo, on the eastern flank of the Tularosa Basin, the potentiometric surface map slopes to the southwest with a hydraulic gradient of 0.01 - 0.0019 (Figure 5). Hydraulic head exceeds 1,340 m along the Sacramento Mountains. Hydraulic head exceeds 1,250 m and hydraulic gradients are about 0.04 along the White Sands re-entrant, a narrow gap between the Organ and San Andres Mountains.

Along the basin floor, the hydraulic gradient is relatively flat (~0.0001) between Alkali Flat and the New Mexico/Texas state line. An almost imperceptible ground-water divide may be present at White Sands that separates ground water recharged north of White Sands from southward flowing ground water that moves into the Hueco Bolson. Ground water moves south from the Tularosa Bolson into the Hueco Bolson and eventually moves into Texas across the state line.

In El Paso County hydraulic gradients are steep (0.02) on the Hueco Mountains and are probably even steeper on the Franklin Mountains. Data are not sufficient to map hydraulic head at the Franklin Mountains. Ground water tends to flow along the axis of the basin toward the Rio Grande, except where large pumping cones of depression beneath the City of El Paso and Ciudad Juárez have reversed the natural hydraulic gradient.

Depth to ground water in the Hueco-Tularosa aquifer is variable. Depth to ground water near the Cities of Tularosa and Alamogordo at the flanks of the Sacramento Mountains is between 6 and 46 m. Drawdowns in many municipal wells, up to 30 m, have been recorded in this area (Figure 5). Ground water is at or near ground surface at Alkali Flat due to evaporative discharge from the wet gypsum playa.

Depth to ground water near the White Sands Missile Range Headquarters, at interior portions of the basin, is up to 122 m. Little drawdown has been recorded there (Figure 6). Drawdowns in the Hueco Bolson near the New Mexico/Texas State line has been relatively small, not exceeding 1.5 to 9 m. Depth to ground water in this area is about 91 to 107 m. Current depth to ground water beneath the City of El Paso is usually between 76 and 122 m at distances from the Rio Grande (Figure 6). Present depth to ground water beneath Ciudad Juárez varies from about 30 to 76 m, except near the Rio Grande where depths are often less than 20 m.

Historical Water Level Trends Along the El Paso/Ciudad Juárez Corridor

In heavily developed parts of the Hueco Bolson, drawdowns since 1940 are up to 45 m. Pumping cones of depression in municipal wellfields are the focal points of drawdown. Most of the drawdowns near municipal wellfields vary between 15 and 30 m (Figure 6). Some of the highest rates of drawdown have occurred beneath Ciudad Juárez; for example, over 30 m of drawdown has been recorded at JMAS-15 in less than 25 years (Figure 6). Steep rates of decline are shown for most of the other municipal wells in Ciudad Juárez. A drawdown map computed with water-level data collected between 1987/1988 and 1992/1993 presents drawdowns in the Hueco Bolson beneath the City of El Paso and Ciudad Juárez (Figure 7). Focal points of drawdown are shown beneath both cities.

Ground-Water Extraction Estimates

Most ground-water discharge from the Hueco Bolson is due to pumping withdrawals for municipal and military water supply. Quantities of ground water pumped from the Hueco Bolson from municipal and other sources have increased by a factor of almost 6 since 1950 (Figure 8). Recent trends indicate that municipal pumpage in Mexico increased about 12.5% between 1990 and 1994 (Figure 9). Municipal and military pumpage in the United States decreased 24.0% during the same time interval (Figure 9). Pumping trends reflect the increased dependance on ground water in Mexico, and partial conversion from ground water to surface-water use in the United States.

Current Water Quality (general inorganic constituents)

General water quality of the Hueco - Tularosa aquifer is shown in the regional stiff map (Plate 1). This map used very recent water quality data in areas where extensive ground-water development has occurred, and both historical and recent data in areas where there has been little current and historical ground-water pumpage. Comparison of multiple samples collected from the same water well over several decades indicates that most analyses do not change significantly when the aquifer is not developed. Historical data are therefore, considered to be good proxy data for current water quality in areas where the aquifer has not been pumped significantly.

Ground water north of the New Mexico/Texas State line is usually greater than 1,000 mg/L TDS except in mountains and along mountain fronts, where ground waters are dilute. Many samples along the interior of the basin at or just south of Alkali Flat have TDS greater than 10,000 mg/L. Near and extending across the state line to the Rio Grande alluvium, ground waters along the Franklin Mountains are characteristically less than 700 mg/L TDS (Plate 1). Basinward of the recharge areas along the Franklin Mountains salinities increase to over 1,000 mg/L in many wells, reaching concentrations over 1,500 mg/L in wells along the axis of the basin. Salinities of ground water underlying the Ciudad Juárez area are generally less than 1,000 mg/L.

Several sets of hydrochemical analyses are clustered according to distinct hydrochemical groupings (Figure 10). They include (1) mountain and mountain front samples along the Sacramento Mountains; (2) mountain and mountain front and gypsum playa samples along and below the San Andres and Organ Mountains; (3) mountain front samples along the Franklin Mountains; (4) basin floor samples in the Hueco Bolson (New Mexico, Texas, and Mexico); and (5) samples from Ciudad Juárez municipal wells.

The mountain and mountain front samples along the Sacramento Mountains (group 1) cluster mostly as Ca-HCO3-SO4 and Ca-Cl-SO4 waters, except for ground waters high in the Sacramento Mountains which are Ca-HCO3 ground waters. Ground waters with greater than 1,000 mg/L TDS have a Ca-Cl-SO4 signature, and ground waters with less than 1,000 mg/L TDS have a Ca-HCO3-SO4 signature.

The mountain and mountain front samples in group 2 are Ca-HCO3 and mixed cation-HCO3-SO4 type ground waters with TDS less than 1,000 mg/L. Eastward along the basin floor, ground waters have a strong Na-Cl-SO4 and mixed cation-SO4-Cl signature and salinities mostly greater than 10,000 mg/L (Plate 1). The high-TDS ground waters are just south of Alkali Flat, a gypsum playa, and are drawn from earlier gypsum-playa deposits (USBR, 1984). These hydrochemical signatures are commonly observed where evaporite minerals are dissolved in great quantity.

Along the Franklin Mountains are dilute, Na-HCO3 and Na-HCO3-Cl type ground waters (group 3). Chloride increasingly becomes a dominant anion basinward of this mountain recharge area.

Down gradient from group 3 wells, samples from group 4 wells suggest continued hydrochemical evolution. Group 4 ground waters have higher TDS, higher percentages of Cl and SO4, and lower concentrations of HCO3 than upgradient waters. These are principally Na-Cl and Na-Cl-SO4 ground waters. TDS is usually less than 1,000 mg/L just east of the Franklin Mountains and is generally greater than 1,000 mg/L along the axis of the basin.

Group 5 samples were collected from Ciudad Juárez municipal wells. Ground waters are Ca-Na-mixed anion to Na-Cl-SO4 type ground waters with salinities less than 1,000 mg/L TDS. Ca-Na dominated waters are located at distances from the river, and Na-dominated waters are commonly found near the Rio Grande.

Historical Water Quality Trends (general inorganic constituents)

Chloride has increased over time in many of the municipal wells in El Paso and Ciudad Juárez (Figure 11). The chloride/water-level hydrographs do not show a perceptible pattern of increasing chloride with respect to location, although a clear pattern is shown for salinization of wells that have had significant long-term drawdowns. Chloride now exceeds 250 mg/L in several of the wells in the area (Figure 11).

Hydrochemical graphs shown in time series indicate how the overall chemistry of water collected from some wells in the Hueco Bolson has changed with time (Figure 12). Samples derived from 49-05-503 indicate that the well has experienced increasing chlorinity and little change in the concentration of other ions (Figure 12). The well screen is 110 to 174 m beneath land surface. Samples taken from 49-13-610 indicate that the chemistry from the well has had substantial increases in sulfate, sodium, and chloride. The well screen is between 88 and 229 m beneath land surface at the well. Samples taken from 49-22-408 have changed the most with respect to TDS, and had a marked upward trend in concentration of sodium and chloride (Figure 12). This well is located near the Rio Grande and is screened between 105 and 162 m. JMAS-15, a Ciudad Juárez municipal well, has seen moderate increases in most ions, especially sulfate and chloride. JMAS-39 has had even greater increases in ions, especially bicarbonate, sulfate, sodium, and chloride. JMAS-43 has had an especially large increase in the concentration of sulfate since 1973.

SOUTHEASTERN HUECO AQUIFER

Location and Extent

The southeastern Hueco Bolson is separated geographically from the Hueco-Tularosa Bolson at the El Paso/Hudspeth County line (Figure 13). A southeast trending linear feature, the bolson extends for 88 km from the El Paso/Hudspeth County line to its southeastern limit at Indian Hot Springs. The bolson is bounded on the north by the Finlay, Malone, and Quitman Mountains and Diablo Plateau. The Sierra de San Ignacio, Sierra de El Almagorsa, Sierra de San Jose Del Prisco, Sierra de Las Vacas, and Sierra de Carrizalillo define its southern boundary (Figure 13). Total surface area of the southeastern Hueco Bolson is 2,150 km^2. Approximately 61% of its land area is in the United States.

North of the river, the floor of the bolson slopes toward the southwest, from elevations of 1,400 to 1,100 m near the Diablo Plateau escarpment and Quitman Mountains to elevations of 1,080 to 1,005 m along the Rio Grande. South of the river, the floor of the bolson slopes from elevations of 1,356 to 1,250 m along mountain fronts to the Rio Grande. The Rio Grande is the only perennial river between county line and Indian Hot Springs. A few springs in the mountains provide localized flows and seeps, but most surface flows in the highlands are ephemeral and are focused at arroyos which carry water only after heavy rainfall.

Saturated rocks in the highlands are recharged by precipitation (Figure 14). The Cenozoic basin fill, in turn, is recharged partially from Cretaceous and Tertiary rocks by cross-formational flow (Kreitler and others, 1986). That the interconnected bedrock-and-basin fill aquifers form an integrated *flow system requires definition of aquifer nomenclature. Herein the term "southeastern Hueco aquifer" refers to the saturated bolson and interconnected bedrock units that flank and underlie the southeastern Hueco Bolson. Ground-water divides in the mountains and plateaus define the limits of basinward recharge areas and the geographical limits of the aquifer (Figure 13).*

Basin geometry and Rock and Sediment Types

The oldest principal hydrostratigraphic units in the southeastern Hueco aquifer are the Cretaceous carbonate and clastic rocks (Figure 14) that are exposed in the highlands and lie uncomformably beneath the bolson sediments (Fisher and Mullican, 1990). Data are insufficient to determine if these consolidated rocks act as a single hydrostratigraphic unit or as a series of discontinuous and poorly interconnected hydrogeologic strata (Fisher and Mullican, 1990). The extensive tectonic history of the region and intense faulting, fracturing, and folding of Cretaceous strata may suggest that the rocks act as a heterogeneous, interconnected double continuum media with one continuum representing weakly-to-strongly interconnected fractures and the other representing the porous rock matrix. Evidence of extensive karstification of Cretaceous rocks is lacking in this area although Permian rocks to the northeast, in the Dell City area, show considerable karstification in outcrop and core.

The Cenozoic basin-fill sediments, which make up the second major water-bearing unit (de la O Carreno, 1957; Mullican and Senger, 1992) consist of minor sand lenses interstratified in a matrix of clay and silty-clays. Depositional environments ranged from alluvial fans to ephemeral lakes and saline playas (Gustavson, 1990). Vertical offset by Basin and Range faults and tabular and lenticular geometries of sand, silt, and clay deposits create significant intrastratigraphic discontinuities (de la O Carreno, 1957; Geo Fimex, 1970; Fisher and Mullican, 1990).

The thickness of the basin fill decreases from as much as 2,600 m at the El Paso/Hudspeth County line to an infinitesimal thickness where the bolson thins out near Indian Hot Springs (Collins and Raney, 1991). Saturated bolson fill is principally the lower basin fill series. The lower basin fill is mostly lacustrine clay, bedded gypsum, and minor sand, silt, and clay from both alluvial fans and local fluvial deposits (Geo Fimex, 1970; Collins and Raney, 1991). The upper basin fill series, a second lithologic unit, is thin and contains little water east of the El Paso/Hudspeth County line. The upper basin fill deposits were formed in alluvial fan, fluvial, and lacustrine systems and are composed of sand and gravel and minor silt and clay. They are separated from the lower basin fill series by an uncomformable contact as much as 2.5 m.y. old (Vanderhill, 1986).

These trends are shown by the electrical resistivity cross section B - B' in Mexico (Figure 15). Vertical electrical soundings performed parallel to Rio Grande showed that aquifer resistivities are up to 100 ohm-m only in the upper 50 meters of bolson fill, which are mostly unsaturated materials in the region south of the Rio Grande floodplain (Figure 15). At depths between 100 and 500 meters, the electrical resistivity values are usually less than 5 ohm-m. Such low values imply clay-dominated strata, or strata saturated with slightly to moderately saline pore fluids (de la O Carreno, 1958; Dobrin, 1976; Kearey and Brooks, 1984). Resisitivty increases to 8 to 10 ohm-m between 500 and 1,000 m, and then increases to greater than 40 to 50 ohm-m between 800 and 1,000 m, suggesting bedrock of probable Cretaceous age.

The Quaternary alluvium and terrace deposits were formed by deposition by the Rio Grande. These deposits and their hydrogeologic characteristics are discussed in the next section, entitled "Rio Grande Aquifer."

Water Levels

North of the Rio Grande, the regional potentiometric surface map shows high hydraulic heads and ground-water divides along the Diablo Plateau, Finlay Mountains, and Quitman Mountains (Figure 16). Areas of high head in the mountains and plateaus define focal points of recharge in the southeast Hueco aquifer. Hydraulic head gradients in the Cretaceous and other bedrock strata are as much as 0.07 along ground-water divides and are as little as 0.04 along mountains fronts. Hydraulic gradients in the bolson fill are about 0.008.

South of the Rio Grande, the potentiometric surface slopes to the river from high topographic elevations along mountain fronts. Peak elevations of the mountain ranges probably mark the location of ground-water divides. Springs flow at high elevations from the mountains in Mexico. These probably discharge from locally perched flow systems that do not define hydraulic head in the zone of regional saturation. Data are not adequate to define regional hydraulic heads beneath these mountains. Hydraulic gradients south of the Rio Grande are about 0.01 to 0.03.

Depth to ground water in the southeastern Hueco aquifer is highly variable. The depths measured to the regional water table in Cretaceous rocks varied from 23 to 191 m, except at Thaxton Spring where ground water flows at land surface at the Diablo Plateau escarpment. Depth to ground-water in the basin fill was measured between 28 and 146 m (Mullican and Senger, 1992). Depth to ground water beneath mountain ranges that bound the southeastern Hueco Bolson in Mexico is unknown.

The southeastern Hueco aquifer can almost be considered undeveloped, especially north of the Rio Grande. Low capacity domestic and livestock wells are used to satisfy the needs of the local population and livestock industry. Water-level data in time series are not available in the southeastern Hueco aquifer.

Water Quality (general inorganic constituents)

A stiff diagram (Plate 1) illustrates general water quality in the southeastern Hueco aquifer. Total dissolved solids are typically greater than 1,000 mg/L in the mountains, increasing to as much as 4,000 mg/L in the bolson. Ground water chemistry in the Rio Grande aquifer is discussed independently in the next section.

The hydrochemical facies (Back, 1966) of southeastern Hueco aquifer ground waters on the United States side of the study area (Figure 17) varies from Ca-Mg-HCO3 and Na-SO4 along the Diablo Plateau to Na-SO4-Cl beneath the floor of the basin. In Mexico, waters vary from Ca-Mg-HCO3 beneath the Sierra de San Ignacio, Sierra de El Almagorsa, and the Sierra de San Jose Del Prisco to Ca-Mg-SO4-Cl waters beneath the basin floor (Figure 17). Typically these ground waters have TDS that vary between 1,000 and 3,500 mg/L. Indian Hot Springs is an exception; Na-Cl water with TDS higher than 7,000 mg/L discharges from Cretaceous carbonate and clastic rocks at the hot springs.

RIO GRANDE AQUIFER

Location and Extent

Near the southeastern limit of the Mesilla Valley, the Rio Grande is constricted between the Cerro de Muleros and the Franklin Mountains in a canyon, the El Paso narrows. Here the canyon is about 450 m wide. Rock cut terraces are visible on the south side of the river that rise a few hundred feet above the modern channel.

Southeast of the El Paso narrows, the Rio Grande flows across a broad alluvial floodplain that has incised the surface of the Hueco Bolson (Figure 18). Near El Paso/Ciudad Juárez, the "El Paso/Juárez Valley" is about 9.7 to 13 km wide and is a little more than 60 m deep (USBR, 1973). The valley trends nearly 145 km east, southeast to Indian Hot Springs where the valley again is constricted in a narrow between the Sierra de la Cieneguilla and the Quitman Mountains. The valley deepens along its southeasterly trend and is almost 100 m deep near Fabens, 48 km below the El Paso narrows. The valley wall is disrupted frequently by arroyos that incise the Hueco Bolson and floodplain surfaces. Our analysis extends to a few kilometers downstream of Fort Quitman, where the Rio Grande floodplain becomes very narrow (Figure 18).

Sediment Types

The Rio Grande alluvial floodplain in the El Paso/Juárez Valley is underlain by a complex mosaic of braided and meandering river deposits. Formed during alternating periods of scour and fill in the late Quaternary Period, the river deposits consist of irregularly distributed gravels, sands, clay, and silt lenses and beds (de la O Carreno, 1957, 1958; USBR, 1973; Alvarez and Buckner, 1980). Lenses and beds are highly irregular in extent and thickness and correlations across short distances are difficult or impossible to make with available data.

Alluvial fill consists of reworked bolson fill material, eroded bedrock, and extrabasinal sediments transported by the Rio Grande from its headwaters in New Mexico and Colorado to the El Paso/Juárez Valley. Total thickness of the Rio Grande alluvium is reported to average about 64 m in the United States (IBWC, 1989). Average thickness is about 52 m in Mexico (IBWC, 1989). Saturated alluvium thicknesses average 57 and 45 m respectively in the American and Mexican portions of the alluvial floodplain, El Paso/Juárez Valley (IBWC, 1989).

Windblown sand and silt deposits overlie the Rio Grande alluvium at several localities. Where dunes and other windblown deposits are present, they often border the outer margins of the Rio Grande floodplain. Most dunes are less than 4.5 m thick (IBWC, 1989). Windblown deposits are surfaces for infiltration and recharge because they are well sorted and sparsely vegetated.

Recharge

Recharge to the Rio Grande aquifer along irrigated reaches is due primarily to infiltration of surface water that has been applied to irrigable crops (Figure 19). Major ion data shows clear evidence of direct recharge due to surface irrigation. Texas State well #48-41-624, for example, had increasing salinities between 1986 and 1988 (Figure 20). When the well was resampled in 1989, total dissolved solids had decreased substantially. A chemical trilinear plot (Figure 20) indicates dilution of salt-laden ground water due to mixing with dilute Rio Grande water during the 1989 irrigation season.

Recharge also occurs to some extent by direct seepage from canal and river channels, although lining of the Rio Grande channel along the Chamizal zone limits recharge by the river locally. Other sources of recharge to the Rio Grande alluvium include direct precipitation on the floodplain surface, seepage from irrigation canals and drains, infiltration of runoff along arroyos, and recharge from cross-formational flow with the Hueco Bolson (Figure 19). Quantification of the amounts and spatial variability of recharge to the alluvial aquifer is infeasible with available data.

Discharge

Ground water is discharged from the Rio Grande alluvium by irrigation pumping, by subsurface seepage to the Rio Grande, by leakage to drains, and by cross-formational leakage to the Hueco Bolson (Figure 19). The principal mode of discharge varies along the floodplain. Along the heavily urbanized Chamizal zone, discharge occurs primarily by cross-formational leakage from the alluvium to the Hueco Bolson where storage in the Rio Grande aquifer is depleted by municipal heavy pumping in the bolson aquifer. From Chamizal zone to the El Paso/Hudspeth County line, discharge occurs by irrigation pumping and by leakage to the many drains which help to maintain nearly constant water-levels in the Rio Grande aquifer. From the county line to Fort Quitman, discharge occurs by irrigation pumping, by seepage to the Rio Grande, and by leakage to a few drains. Phreatophytes account for some discharge along the Rio Grande channel and canal laterals. These channels and canals, in general, are kept relatively free of phreatophytes west of Fort Quitman.

Ground-Water Extraction Estimates

Historical and recent ground-water extraction quantities are not available for the American portion of the Rio Grande aquifer. Estimates are available in Mexico. Quantities include total extraction amounts for wells maintained by CNA, and total extraction quantities for wells maintained by other entities. Figure 21 provides the totals for the years 1989 - 1995. Pumping is greatest between March and August of these years.

Current Water Quality (general inorganic constituents)

Few American ground-water data are available for the Rio Grande aquifer after 1979 below the El Paso narrows. Maps present historical data for the United States portion of the Rio Grande aquifer. Data are current in Mexico (1993 - 1994).

Stiff diagrams indicate sodium-sulfate waters in El Paso County (Figure 22). Below the El Paso/Hudspeth County line, chloride increasingly becomes the dominant anion in the cation/anion pairing (Figure 23). Mexican ground waters follow the same general trend, but show greater scatter in the segment of the floodplain across from Hudspeth County (Figures 22 and 23). Ground-water samples frequently were collected in and beneath arroyo deposits that comformably overlie earlier alluvial floodplain deposits in Mexico. Arroyos act as recharge areas after episodic precipitation and runoff events and ground-water chemistries have wide scatter due to commingling of dilute runoff waters and older alluvial ground waters.

Total dissolved solids in El Paso County vary substantially, but fall mostly within the 1,000 to 3,000 mg/L range (Figure 22). Total dissolved solids are higher in alluvial deposits in Hudspeth County, falling mostly within the 3,000 to 6,000 mg/L range (Figure 23). In both regions, total dissolved solids are lower in the Mexican part of the floodplain aquifer due to mixing of dilute runoff waters with older, higher salinity waters. This is an artifact of well locations closer to arroyos on the floodplain.

Rio Grande Water Quality

Historical monthly water quality and streamflow data show changes in river water quality and discharge between El Paso/Ciudad Juárez and Fort Quitman (Figure 24). Spatial changes in sodium, sulfate, chloride, and total dissolved solids for most months indicate appreciable decline in river water quality downstream. Data indicate that water quality improves when discharge is high during the irrigation season. This is an artifact of dilution by copious quantities of dilute reservoir water and by stagnation of saline baseflow as a result of high river stage. Grouping of analyses fall into distinct clusters (Figures 25 & 26). The "El Paso" and "Fort Quitman" clusters correspond generally to evolutionary trends in the Rio Grande aquifer in and across from El Paso and Hudspeth County respectively (Figure 27). Despite wide scatter in Rio Grande aquifer data (Figure 27), the analyses show a clear relationship between river and aquifer water quality between El Paso and Fort Quitman. Results imply ample fluid exchange and salt recycling between the river and aquifer.

Historical Change

Water quality data are too limited to assess long term changes in the chemistry of the Rio Grande aquifer. Most of the water quality data were collected between 1970 and 1980, an inadequate time interval to assess historical change.

An obvious relationship was shown between salinities and chemistries in the Rio Grande and Rio Grande aquifer between El Paso and Fort Quitman (compare Figures 25, 26, and 27). Historical water quality data from the Rio Grande potentially may be used as proxy data for temporal changes in the Rio Grande aquifer along upstream and downstream segments of the floodplain. Data at the Fort Quitman gage station clearly indicate increasing salinities in the Rio Grande since 1936 (Figure 28). If these are suitable proxy data for historical changes in aquifer water quality, then water in the aquifer has been degraded profoundly during the period of record.

RECOMMENDATIONS

In establishing this binational report and data library, a significant amount of data was acquired, verified, and evaluated. Certain data were incomplete and in some areas information were lacking. The following recommendations are intended to recognize specific data inadequacies, and also to suggest future projects and activities that might enhance our understanding of the local aquifers.

- Wells in Mexico, especially those in the Rio Grande/Rio Bravo alluvium, should be accurately located using GPS equipment. Well head elevations should be determined within an accuracy at least equal to those on the U.S. side (U.S. based on five-foot topographic map contour intervals). This will allow for better regional mapping of ground-water movement.
- Better estimates of irrigation pumpage volumes should be made in the U.S., especially in Texas.
- The thickness of basin fill, storage coefficients, and quantities of fresh and slightly saline ground water in the rural parts of the study area are not well known. Further studies should be conducted to derive better stratigraphic data and better estimates of recoverable ground water in storage.
- Computer ground-water flow models of the Hueco Bolson aquifer currently being developed by Mexico and the U.S. should be supported.
- More data is needed to determine ground-water ages, ground-water residence times, recharge areas, and areas of cross-formational flow. The quality and reliability of the ground-water flow models being developed by the U.S. and Mexico will be enhanced by these data.
- Mechanisms of salinization of heavily developed parts of the Hueco Bolson are not completely understood. Several factors may be responsible for salinization, including brackish water upconing, downconing, leakage along the annular spaces of wells, lateral migration, leakage from mud interbeds, and freshwater depletion. Studies to determine the precise mechanisms of salinization would help the City of El Paso and Ciudad Juárez employ pumping schemes for reduced salinity.
- Some information that Mexico had generated prior to about 1990 was available only in hard copy. This data should be converted to electronic files.
- To continue with the El Paso/Ciudad Juárez area studies, it is recommended that a formal procedure and timetable for binational ground-water data exchange should be established. This data should be recognized for its authenticity by both Mexican and U.S. governments, and should be in an electronic format adaptable for GIS applicants. It is important that this data be made easily accessible.

- A binational aquifer water-level and water-quality monitoring network should be established. Monitoring frequency and procedural protocol should be agreed upon and subsequent data should be shared on a continuous real-time basis.
- The binational technical work group established for this project should extend this work, so as to include more input on the hydrogeologic properties and processes operative in the transboundary aquifers, and to seek technical solutions to common ground-water problems.

REFERENCES

Alvarez, H.J., and Buckner, A.W., 1980, Ground-water development in the El Paso region, Texas, with emphasis on the resources of the lower El Paso Valley: Texas Department of Water Resources Report 246, 346 p.

Back, W., 1966, Hydrochemical facies and ground-water flow patterns in northern part of the Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498-A, 42 pp.

C.I.E.P.S., Engineers, Consultants, and Planners, Mexico City, D.F., 1970, Study of the Technical, Economic, Social, and Financial Feasibility of Rehabilitation of the Irrigation District, Juárez Valley, Chihuahua: Translated by the Ralph McElroy Company, Inc., Austin, Texas, under contract with the Texas Water Development Board, 1975, various pagination.

Garcia, R.A., 1967, Aerial photo geohydrologic study, Juárez Valley, Chihuahua: Ingenieria y Geotecnia, S.A., Translated by Gunnar Brune, Texas Water Development Board, 1975, 19 p.

Collins, E.W., and Raney, J.A., 1991, Tertiary and Quaternary Structure and Paleotectonics of the Hueco Basin, Trans-Pecos Texas and Chihuahua, Mexico: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 91-2, 44 p.

Davis, M.E., and Leggat, E.R., 1967, Preliminary results of the investigation of the saline-water resources in the Hueco bolson near El Paso, Texas: U.S. Geological Survey open-file report, 27 p.

de la O Carreno, A., 1957, Preliminary geohydrological study of the Juárez Valley and surrounding areas, State of Chihuahua: Mexico City, D.F., 101 p.

de la O Carreno, A., 1958, Investigation of subsurface geohydrologic conditions at Juárez, Chihuahua, applying electrical geophysics: Mexico City, D.F., 55 p.

Dobrin, M.B., 1976, Introduction to Geophysical Prospecting: McGraw-Hill Book Co., New York, 630 p.

Fisher, R.S, and Mullican, W.F., III, 1990, Integration of ground-water and vadose-zone geochemistry to investigate hydrochemical evolution: a case study in arid lands of the northern Chihuahuan Desert, Trans-Pecos, Texas: The University of Texas at Austin Bureau of Economic Geology Geological Circular 90-5, 36 p.

Geo Fimex, S.A., 1970, Valle De Juárez, Chihuahua, Estudio Geofisico: Sociedad de Reconocimientos Geotecnicos Del Grupo S.R.G., Coyocan, Mexico, 16 p.

Gustavson, T.C., 1990, Regional stratigraphy and geomorphic evolution of the southern Hueco Bolson, west Texas and Chihuahua, Mexico, *in Hydrogeology of Trans-Pecos Texas, Bureau of Economic Geology Guidebook 25, p 27 - 35.*

International Boundary and Water Commission, 1989, Ground water conditions in El Paso/Juárez Valley: Hydraulics Branch, Planning Division, 43 p.

Kearey, P., and Brooks, M., 1984, An Introduction to Geophysical Exploration: Blackwell Book Co., Oxford, 296 p.

Kreitler, C.W., Raney, J.A., Nativ, R., Collins, E.W., Mullican, W.F., III, Gustavson, T.C., and Henry, C.D., 1986, Preliminary geologic and hydrologic studies of selected areas in Culberson and Hudspeth Counties, Texas: final report for the Texas Low-Level Radioactive Waste Disposal Authority under contract no. IAC(86-87)0818, 184 p.

Lee Wilson and Associates, Inc., 1986, Water supply alternatives for El Paso: Unpublished consultant's report prepared for the El Paso Water Utilities Public Service Board, 75 p.

Meyer, W.R., 1976, Digital model for simulated effects of ground-water pumping in the Hueco Bolson, El Paso area, Texas, New Mexico, and Mexico: U.S. Geological Survey Water-Resources Investigations Report 58-75, 31 p.

McLean, J.S., 1970, Saline Ground-Water Resources of the Tularosa Basin, New Mexico: U.S. Department of the Interior, Office of Saline Water, Research and Development Progress Report No. 561.

Mullican,W.F., III, and Senger, R.K., 1992, Hydrogeologic investigations of deep ground-water flow in the Chihuahuan Desert, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 205, 60 p.

Orr, B.R., and Risser, D.W., 1992, Geohydrology and potential effects of development of freshwater resources in the northern part of the Hueco Bolson, Dona Ana and Otero Counties, New Mexico, and El Paso County, Texas: U.S. Geological Survey Water-Resources Investigations Report 91-4082, 92 p.

Sandeen, W.M., 1954, Geology of the Tularosa Basin, New Mexico, *in Guidebook of southeastern New Mexico: New Mexico Geological Society, 5th Field Conference, p. 81-88.*

Slichter, C.S., 1905, Observations on the ground waters of Rio Grande Valley: U.S. Geological Survey Water Supply Paper 141,

Strain, W.S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: University of Texas at Austin, Memorial Museum Bulletin 10, 55 p.

U.S. Bureau of Reclamation, 1973, Water Resources of El Paso County, Texas: Rio Grande Project, New Mexico - Texas Project Office, El Paso, Texas, 97 p.

U.S. Bureau of Reclamation, 1984, Tularosa Basin Water and Energy Study, New Mexico, Appraisal Report: Southwest Regional Office, Amarillo, Texas, various pagination.

Vanderhill, J.B., 1986, Lithostratigraphy, vertebrate paleontology, and magnetostratigraphy of Pleistocene sediments in the Mesilla Basin, New Mexico: The University of Texas at Austin, Ph.D. dissertation, 305 p.

Wilkins, D.W., 1986, Geohydrology of the southwest alluvial basins regional aquifer-systems analysis, parts of Colorado, New Mexico, and Texas: U.S. Geological Survey Water-Resources Investigations Report 84-4224, 61 p.

FIGURE CAPTIONS

Figure 1. Location of the Hueco-Tularosa aquifer, southeastern Hueco aquifer, and Rio Grande aquifer in the regional study area.

Figure 2. Location and extent of the Hueco-Tularosa aquifer in the study area.

Figure 3. Hydrogeologic cross-sections A-A', B-B', and C-C' across the Hueco-Tularosa aquifer (lines of sections shown on Figure 2. Basin fill/bedrock contacts selected from maps prepared by Davis and Legatt, 1967, McLean, 1970, and Lee Wilson and Associates, 1981. Cross section C-C' modified from Lee Wilson and Associates, 1981).

Figure 4. Geoelectric cross-section D-D' across the Hueco-Tularosa aquifer, northern Chihuahua, Mexico (modified from Geo Fimex, 1970; line of section shown on Figure 2).

Figure 5. Regional potentiometric surface map for the Hueco-Tularosa aquifer, illustrating an inset potentiometric surface map for the City of El Paso and Ciudad Juárez. Data for the City of El Paso and Ciudad Juárez inset diagram gathered in 1994. Other data in less developed and undeveloped areas gathered at various times. We assume quasi-steady state ground-water flow in undeveloped areas (source of data, Comisión Nacional Del Agua; Junta Municipal de Agua y Saneamiento; Instituito Nacional de Estadistica, Geografia e Informatica; Texas Water Development Board; U.S. Geological Survey).

Figure 6. Time series hydrographs for the Hueco-Tularosa aquifer (source of data, Junta Municipal de Agua y Saneamiento; Texas Water Development Board; U.S. Geological Survey).

Figure 7. Change in water levels for the City of El Paso - Ciudad Juárez area, 1987/1988 to 1992/1993 (source of data, Texas Water Development Board; City of El Paso Public Services Board; Junta Municipal de Agua y Saneamiento).

Figure 8. Ground-water pumpage from the Hueco Bolson; 1903 - 1994 (source of data, City of El Paso Public Services Board).

Figure 9. Ground-water pumpage from the Hueco Bolson; 1990 - 1994 (source of data, Junta Municipal de Agua y Saneamiento; City of El Paso Public Services Board).

Figure 10. Piper diagrams illustrating geochemical types for the Hueco-Tularosa aquifer (source of data, Comisión Nacional Del Agua; Junta Municipal de Agua y Saneamiento; Instituito Nacional de Estadistica, Geografia e Informatica; Texas Water Development Board; U.S. Geological Survey).

Figure 11. Comparison of change of chloride concentration in ground water with drawdown in City of El Paso and Ciudad Juárez municipal water wells (source of data, Texas Water Development Board; Junta Municipal de Agua y Saneamiento).

Figure 12. Time series hydrochemical plots for municipal wells in City of El Paso and Ciudad Juárez showing increasing concentrations of major elemental constituents in ground water (source of data, Junta Municipal de Agua y Saneamiento; Texas Water Development Board).

Figure 13. Location and extent of the southeastern Hueco aquifer.

Figure 14. Generalized hydrogeologic cross section A - A' (line of section shown in Figure 13. Basin fill/bedrock contact selected from maps prepared by Collins and Raney, 1991 and from test-hole logs and geophysical logs in the Texas Water Development Board files).

Figure 15. Geoelectric cross section B - B' across the southeastern Hueco aquifer, northern Chihuahua, Mexico (modified from Geo Fimex, 1970; line of section shown on Figure 13).

Figure 16. Regional potentiometric surface map for the southeastern Hueco aquifer. U.S. data collected 1970 - 1989 and Mexico data collected 1982 - 1983. We assume quasi-steady state ground-water flow in the southeastern Hueco aquifer, which is mostly undeveloped (source of data, Texas Water Development Board; Fisher and Mullican, 1990; Comisión Nacional Del Agua; Instituito Nacional de Estadistica, Geografia e Informatica).

Figure 17a. Hydrochemical piper plots for the bedrock (mountain and plateau) strata, bolson strata, and Indian Hot Springs in the U.S. part of the southeastern Hueco aquifer. Data collected 1986 - 1989. Piper plots indicate distinct hydrochemical types for these water bearing strata in the southeastern Hueco aquifer (source of data, Fisher and Mullican, 1990; Texas Water Development Board).

Figure 17b. Hydrochemical piper plots for the bedrock (mountain) strata, and bolson strata in the Mexican part of the southeastern Hueco aquifer. Data collected 1982 - 1983. Piper plots indicate distinct hydrochemical types for these water bearing strata in the southeastern Hueco aquifer (source of data, Comisión Nacional Del Agua; Instituito Nacional de Estadistica, Geografia e Informatica).

Figure 18. Location of the Rio Grande aquifer in the study area.

Figure 19. Major flow components in the Rio Grande aquifer.

Figure 20. Located adjacent to the Rio Grande, well 48-41-624 had increasing total dissolved solids in samples collected between 1986 and 1988. When the well was resampled in 1989, total dissolved solids had decreased substantially. The trilinear plot shows enriched well samples (1986-1988), dilute well samples (1989), and Rio Grande samples collected in 1989. Results indicate dilution of ground water due to mixing with Rio Grande water (source of data, Fisher and Mullican, 1990).

Figure 21. Extraction quantities from the Rio Grande aquifer; CNA and other wells, 1989 - 1995 (source of data, Comisión Nacional Del Agua).

Figure 22. Stiff plots show Na-SO4 ground waters with salinities usually less than 3,000 mg/L in the Rio Grande aquifer above the El Paso/Hudspeth County line (source of data, Texas Water Development Board; Comisión Nacional Del Agua).

Figure 23. Stiff plots show Na-SO4-Cl ground waters with salinities usually greater than 3,000 mg/L in the Rio Grande aquifer below the El Paso/Hudspeth County line (source of data, Texas Water Development Board; Comisión Nacional Del Agua).

Figure 24a. Diagram comparing water quality and streamflow discharge in the Rio Grande at El Paso and Ft Quitman, 1973. Spatial changes in Na, SO4, Cl, and TDS for most months indicate appreciable decline in surface water quality downstream of El Paso. Water quality improves when discharge is high as an artifact of dilution by large quantities of dilute reservoir water and by stagnation of saline baseflow as a result of high river stage (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

Figure 24b. Diagram comparing water quality and streamflow discharge in the Rio Grande at El Paso and Ft Quitman, 1991. Spatial changes in Na, SO4, Cl, and TDS for most months indicate appreciable decline in surface water quality downstream of El Paso. Water quality improves when discharge is high as an artifact of dilution by large quantities of dilute reservoir water and by stagnation of saline baseflow as a result of high river stage (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

Figure 25. Piper diagrams shown in time series that illustrate surface water at the El Paso and Fort Quitman gage stations, January, 1970 - 1991. Surface water groups into distinct clusters of different hydrochemical types at the two gage stations (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

Figure 26. Piper diagrams shown in time series that illustrate surface water at the El Paso and Fort Quitman gage stations, July, 1970 - 1991. Surface water groups into distinct clusters of different hydrochemical types at the two gage stations (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

Figure 27. Piper diagrams for the Rio Grande aquifer in El Paso and Hudspeth counties, and adjacent areas in Mexico. U.S. data collected 1972 - 1979 and Mexico data collected 1993 - 1994. These data indicate a clear relationship to surface water quality (Figures 25 and 26) at El Paso and Fort Quitman (source of data, Texas Water Development Board; Comisión Nacional Del Agua).

Figure 28. Time series graph of increasing salinities in the Rio Grande (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

The figures and tables that complement the Transboundary Aquifers and Binational Ground-Water Data Base Report are not available on the Internet. The entire report is available at the U.S. International Boundary and Water Commission library.

For further information contact:
Radu Boghici
Hydrogeologist
Texas Water Development Board
(512) 463-6543

Or Contact:
Rong Kuo Ph.D.
Civil Engineer
(915) 832-4747