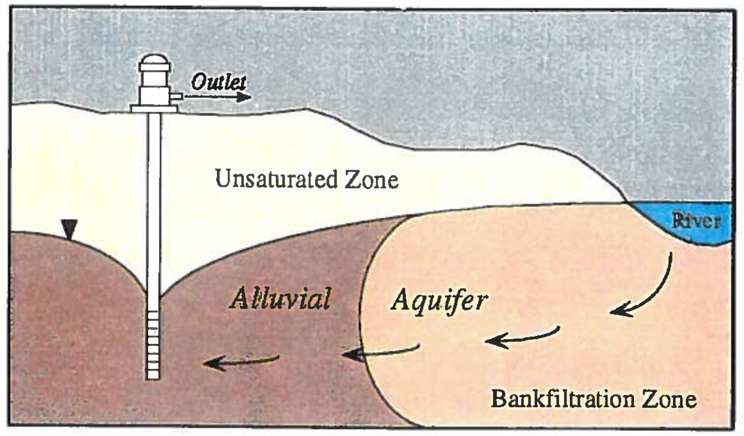
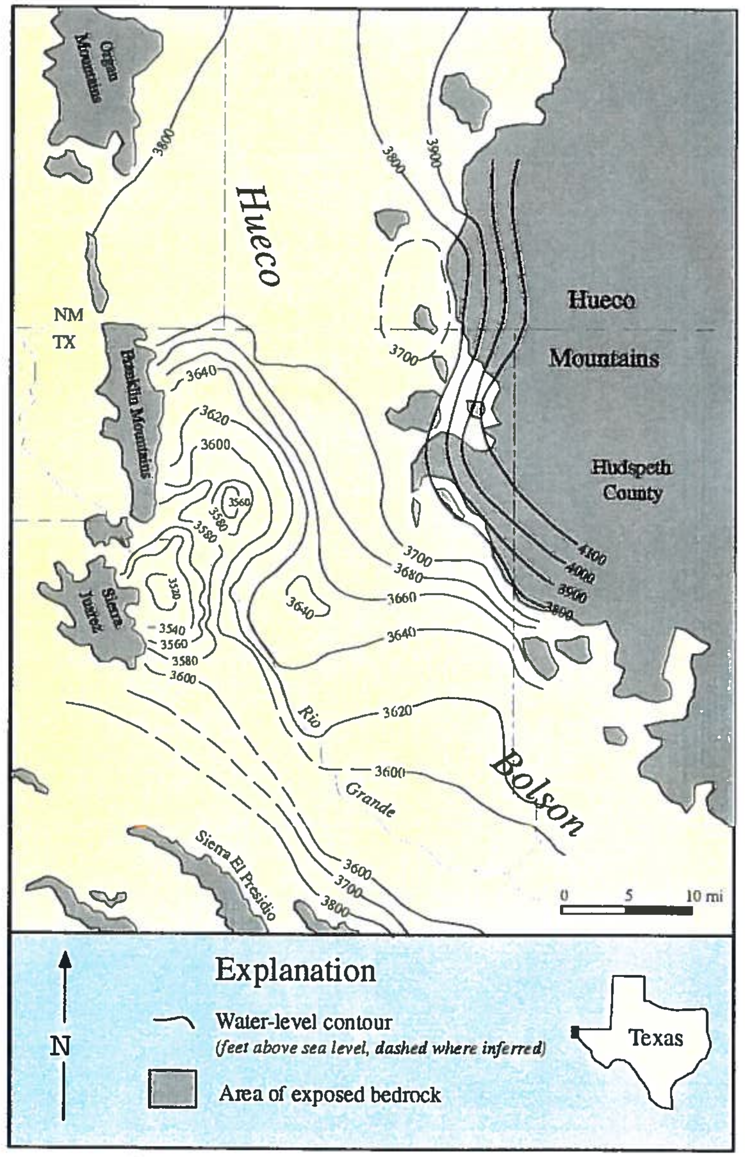




Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region

Prepared By

Texas Water Development Board
New Mexico Water Resources Research Institute

New Mexico Water Resources Research Institute

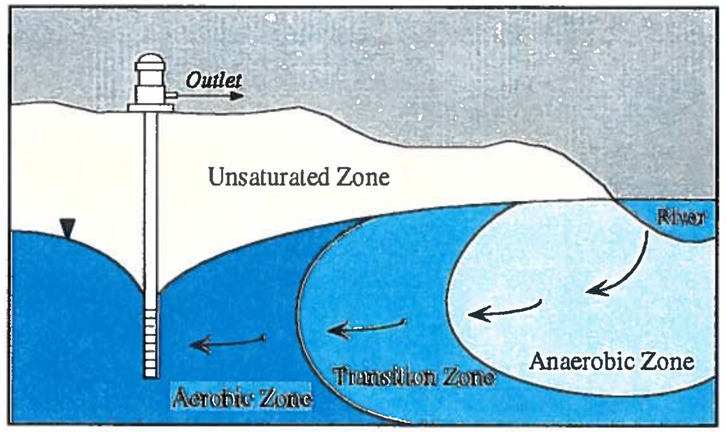
In Cooperation With

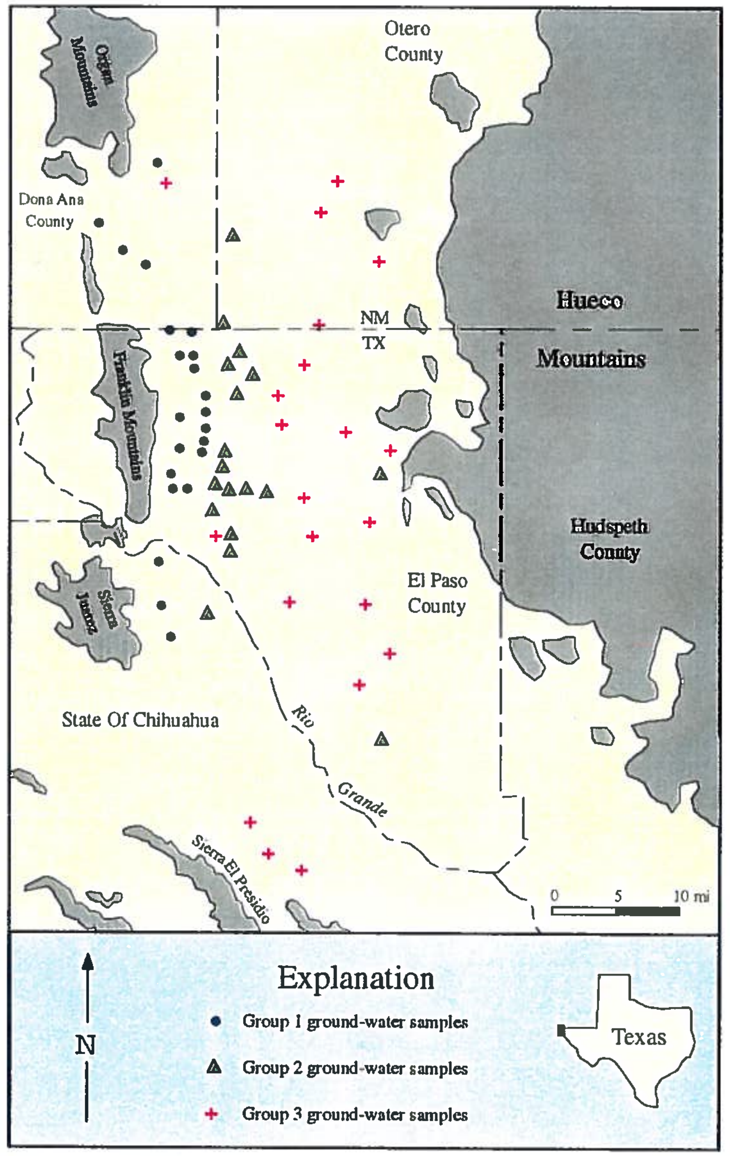
Comision Nacional Del Agua
Junta Municipal de Agua y Saneamiento de Ciudad Juarez
International Boundary and Water Commission
Comision International de Limites y Aguas

Prepared For

U.S. Environmental Protection Agency, Region VI

October, 1997





Prepared By

Texas Team Participants

Barry J. Hibbs, Principal Hydrogeologist; Radu N. Boghici, Hydrogeologist; Mark E. Hayes, GIS Analyst; John B. Ashworth, Project Manager/Geologist

New Mexico Team Participants

Adrian T. Hanson, Environmental Engineer; Zohrab A. Samani, Hydrogeologist; John F. Kennedy, GIS Analyst/Geologist; Bobby J. Creel, Project Manager

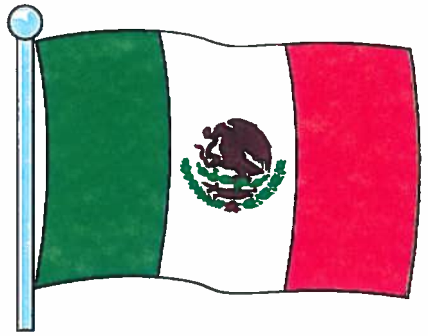
GIS Section (Appendix C) By

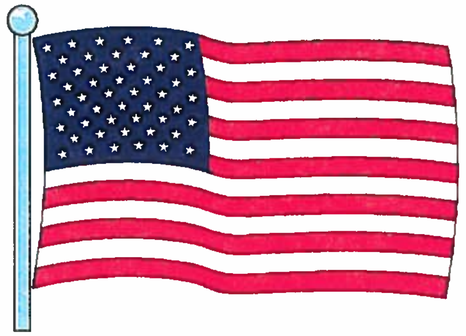
Texas : Mark Hayes, Darrell Peckham, Erika Boghici
New Mexico: John F. Kennedy

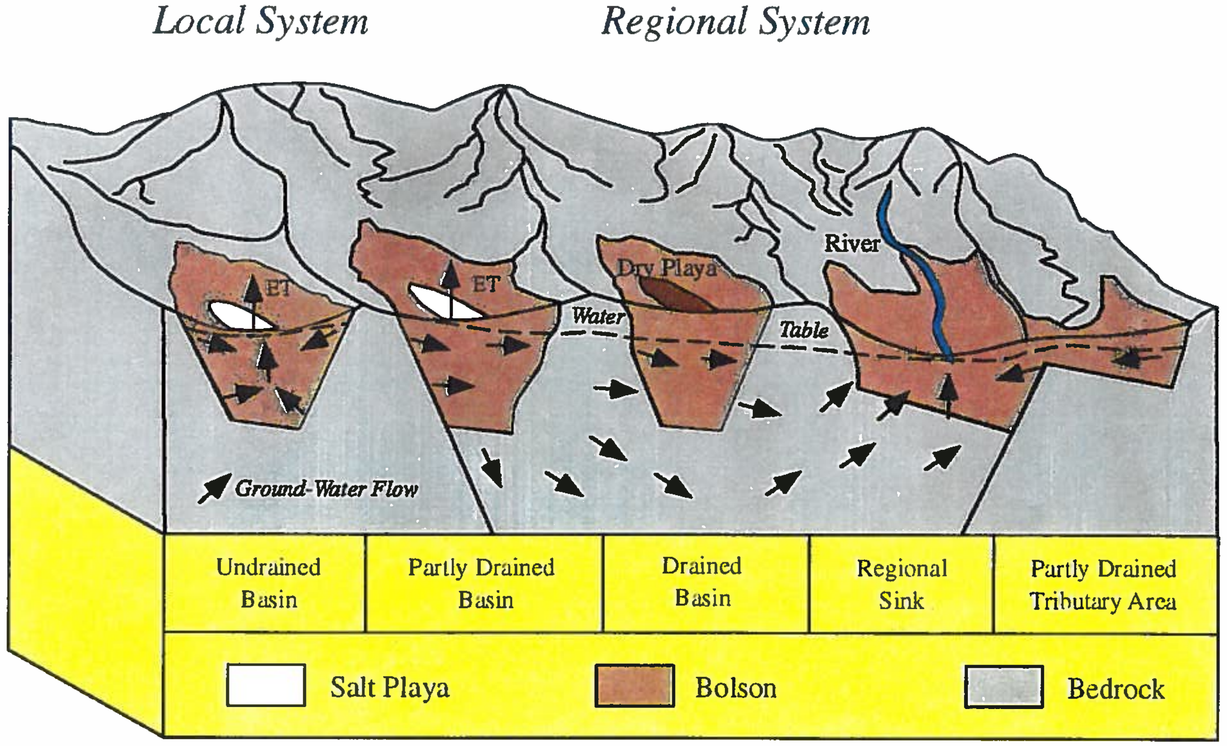
Cartographic and Technical Assistance By

Texas : Steve Gifford, Steve Moore, Steve Segura, Jay Galvan, Mike McCathern, Frank Bilberry
New Mexico: Pamela Hann, Kenny Stevens

Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region







Project Management

Kenneth W. Williams, Michael Vaughan
Project Officers
U.S. Environmental Protection Agency, Region VI

John B. Ashworth, Barry J. Hibbs
Project Managers, Texas Team
Texas Water Development Board

Bobby J. Creel
Project Manager, New Mexico Team
New Mexico Water Resources Research Institute

Final Report

Joint contract report prepared by the Texas Water Development Board, Water Supplies/GIS Sections, and New Mexico Water Resources Research Institute for the U.S. Environmental Protection Agency, Region VI, under interagency contract numbers X 996343-01-0 and X 996350-01-0

EXECUTIVE SUMMARY

At the request of the U.S. Environmental Protection Agency, the Texas Water Development Board and the New Mexico Water Resources Research Institute undertook this study to characterize binational aquifers in parts of far west Texas, south central New Mexico, and northeastern Chihuahua, Mexico. The study area lies along a corridor centered at the City of El Paso\Ciudad Juarez metroplex and extending 62 mi (100 km) on either side of the international border. Assessments were made of the Mesilla Basin ground-water aquifer system, Rio Grande aquifer (Leasburg Dam to Indian Hot Springs), Hueco-Tularosa aquifer, southeastern Hueco aquifer, and Diablo Plateau aquifer. Technical and administrative assistance and data were provided by the Comision Nacional Del Agua, Junta Municipal de Agua y Saneamiento de Ciudad Juarez, International Boundary and Water Commission, and Comision Internacional de Limites y Aguas.

Many of the surface and ground-water resources along the transboundary corridor are shared between the two nations, yet little binational study of these resources has been undertaken. A number of environmental and hydrologic problems have been identified that will require the cooperation of both nations to solve. Solutions to water-related problems can be derived only when a better understanding of transboundary water resources is attained. This study is an important step toward attaining a better understanding of these binational resources.

To complete this study, data from several sources had to be combined into one data base. GIS coverages of ground water, surface water, and land use attributes were developed from the new data base. Study results for each aquifer are as follows:

Mesilla Basin Ground-Water Aquifer System

- The Mesilla basin ground-water aquifer system (the Rio Grande Floodplain Alluvium, Mesilla Bolson, and the Jornada del Muerto Bolson) are connected hydrologically, however the connections are restricted by aquitards and/or faults and therefore described as separate aquifers. The Mesilla basin aquifer system is an extensive intermontane aquifer system which extends from southern New Mexico to northern Mexico. It is surrounded by mountains which form the boundaries.

- Productive aquifers in the Mesilla basin ground-water system occur in both late Pleistocene to Holocene-Rio Grande alluvium deposits and the upper Tertiary and Quaternary unconsolidated sedimentary deposits of the Santa Fe Group. The surface water system is comprised of the Rio Grande and its tributaries and a network of canals, laterals and drainage ditches that discharge to the river. The surface drainage of the Mesilla basin covers approximately 11,000 square miles.

- Total water use in 1990, both surface water and ground water, for all categories was about 513,841 acre-feet of which 145,663 was from ground-water sources. Depletions were 246,279 acre-feet of which 96,895 was from ground water.

- There are two major potential sources of ground-water contamination which might impact the Mesilla Bolson: agricultural activity and high density residential septic tanks. The agricultural activity can again be broadly sub-divided into two major impact categories: cropping and dairies. The cropping activities which may have a negative impact on the ground water are: fertilization practices, pesticide and herbicide use, and irrigation practices. The number of milk cows in Doña Ana County in 1994 was estimated to be 31,000 and are largely concentrated south of Las Cruces along the eastern border of the Mesilla Bolson. Of the estimated 40,000 residents of southern Doña Ana County, New Mexico, fewer than 7% are on sewered wastewater systems. The majority use on-site waste treatment systems.

- The Rio Grande Floodplain Alluvium, between Leasburg dam and the El Paso narrows, is not a confined aquifer and consists of alternating and interfingering layers of clay and fluvial facies. These deposits extend laterally for hundreds of feet beyond the valley slopes with a basal gravel layer about 30 to 40 feet thick. It generally runs the width of the valley and is approximately 80 feet deep. The water table is approximately 10 to 25 feet below the land surface. Ground water within the alluvium is generally unconfined and typically moves southeastward down the valley at an average gradient of about 4 to 6 feet per mile; however, the direction is somewhat influenced by nearby hydraulic structures such as the river, drains, canals, well pumpage and heavily irrigated fields. Recharge to the aquifer occurs primarily as vertical flow from the surface water system (river, canals, laterals, and drains) and irrigated cropland fields. The quality of the water generally reflects the quality of the surface water system, ranging from about 500 TDS to over 1,000 TDS. The majority of discharge from the floodplain alluvium occurs through evapotranspiration of irrigated crops, flow to drain system, irrigation pumpage, municipal pumping, and industrial pumping. Transmissivity values range from 10,000 to 30,000 ft^2/day, hydraulic conductivity of 100 to 350 ft/day, and an estimated specific yield value of 0.2. The specific capacities ranges from 10 to 217 gpm/foot drawdown with an average of 69 gpm/foot drawdown.

- In the Mesilla Bolson the major source of fresh ground water is from the Quaternary-Tertiary age Santa Fe Group. The extent of the aquifer system within the Santa Fe Group is controlled by the surrounding faults which create an effective barrier to ground-water flow, although a small amount of flow may enter or leave the bolson at low barrier points. The Santa Fe Group has thick sequences of clay and silt facies that interfinger with fluvial facies, which create confined/leaky aquifer conditions in the basin fill. These facies vary in depth from 280 feet in the northern part of the bolson to over 2,000 feet near the center of the bolson.

- Three hydrostratigraphic units are commonly referred to: upper unit, middle unit and deep unit. The upper unit is generally only saturated in the northern third of the bolson and consists of gravels with lenticular deposits of clay. This unit may be the most permeable based on larger grain sizes and less cementation. The middle hydrostratigraphic unit is less permeable than the upper unit due to a greater degree of cementation. This unit also consists of gravel and lenticular deposits of clay. The deep unit consists of a uniform fine sand and averages approximately 600 feet in thickness. In general, the basin fill deposits of the Santa Fe Group are deep under the Mesilla Valley and generally thin toward the basin edges. The maximum thickness of Santa Fe Group deposits is estimated as approximately 2,500 feet. The deep hydrostratigraphic group rests on a bedrock of limestone conglomerate which is generally considered impermeable. Hydraulic conductivity's range from 2 - 68 ft/day, 1 - 100 ft/day and 1 - 34 ft/day for upper, middle and deep hydrostratigraphic units respectively. Estimates of transmissivity range from 2,600 ft^2/day for the upper intermediate unit to 4,700 ft^2/day for the deep zones and storage coefficient of 0.00043 in the southern portion.

- In the West Mesa area, the transmissivity of 5,900 ft^2/day was calculated for a well screened at selected intervals between 710 to 1,210 feet. In the northern section of West Mesa the transmissivity was estimated at 10,000 ft^2/day and a storage coefficient of 0.00002. Based on aquifer tests, the transmissivity ranged from 10,900 ft^2/day to 40,000 ft^2/day throughout the bolson. The average horizontal hydraulic conductivity was 67 ft/day. These tests also provided evidence that the horizontal hydraulic conductivity apparently decreases with depth. Vertical hydraulic conductivity values were found to range from 0.21 ft/day to 3.0 ft/day for the entire thickness of the confining layer.

- The majority of recharge occurs through mountain front recharge and through vertical flow of ground water from the floodplain alluvium. The quality of the ground water varies both with depth and areally. The upper unit generally reflects the quality of the alluvium which provides the most significant portion of the recharge, however this varies due to influence of confining clay and silt facies. The middle unit is generally of better quality, but decreases from north to south. This unit is the most heavily developed providing most all of the public and private drinking water supplies. The quality of the deep unit is generally less than the middle unit especially in the southern portion. The majority of the discharge occurs as municipal and industrial pumping.

- The Jornada del Muerto Bolson is east of the Mesilla Bolson. It covers approximately 3,344 square miles and is approximately 12 miles across at its widest section. It does not have a noticeable boundary with the Mesilla Bolson. The two bolsons are separated by a subsurface Tertiary volcanic rock high bounded by normal faults.

- The Santa Fe Group in the Jornada del Muerto Bolson is composed of a fluvial facies, a clay facies, and an alluvial-fan facies. The zone of saturation is most likely in older alluvial-fan deposits or in the fine-grained units of the clay facies. The clay facies is the predominant facies in the zone of saturation in the northern and extreme southern sections of the Jornada del Muerto Bolson. The depth to the water table is between 300 to 575 feet and the thickness of the saturated sediment is between 400 to 500 feet.

- The ground water in the northern part of the bolson moves south down the valley and west at an average gradient of 150 feet per mile. Ground water from the southern part of the bolson moves north and west at an average gradient of 10 feet per mile. The specific capacities for wells in the southern section of the Jornada del Muerto Bolson is about 5 gpm/foot drawdown. Estimated transmissivity values in this area range from 5,000 ft^2/day to 15,000 ft^2/day. Recharge occurs primarily from precipitation and infiltration of mountain runoff through major arroyos. Ground water in the southern section of the Jornada del Muerto Bolson is classified as fresh and water in the northern section of the bolson is classified as slightly saline.

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 4,160 mi^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 Juarez, and for military installations and smaller cities in New Mexico, Texas, and Mexico.

- Well yields in the New Mexico part of the Tularosa-Hueco aquifer vary greatly. Most of the wells produce water from alluvial fans that flank the mountains. Well yields of 1,400 gpm are reported at elevations high on the fans decreasing to 300 to 700 gpm at the lower edges of the fans. Well yields in the mud-rich sediments toward the center of the Tularosa Bolson are usually less than 100 gpm and sometimes less than 15 gpm. South of the New Mexico/Texas State line, well yields in the Hueco Bolson, just east of the Franklin Mountains, are as much as 1,800 gpm. Wells underlying Ciudad Juarez yield from 300 to 1,500 gpm.

- Published hydraulic conductivity values derived from 37 aquifer tests in the Tularosa Bolson vary from 1.0 to 320.0 ft/day. Most wells are installed in alluvial fans. Ranges illustrate the heterogeneity of alluvial fan sediments. Published hydraulic conductivity values derived from 73 aquifer tests in the Hueco Bolson vary from 6.4 to 98.9 ft/day. The range is smaller in the Hueco Bolson and follows a slightly skewed log probability distribution (almost log normal). Comparison of hydraulic conductivity values between the Tularosa and Hueco Bolsons suggest more homogeneous aquifer strata in the Hueco Bolson. Wells in the Hueco Bolson are installed primarily in Camp Rice deposits, a moderately sorted, mostly fluvial deposit. The alluvial fan deposits in New Mexico have a much wider range of hydraulic conductivity due to poor sorting and extreme heterogeneity. Equivalent Camp Rice deposits in the Tularosa Bolson either do not exist or are saturated with saline ground waters and are not developed.

- 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 20 and 150 ft. Drawdowns in many municipal wells, up to 100 ft, 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 400 ft. Little drawdown has been recorded there. Drawdowns in the Hueco Bolson near the New Mexico/Texas State line has been relatively small, not exceeding 30 ft. Current depth to ground water beneath the City of El Paso is usually between 250 and 400 ft at distances from the Rio Grande. Present depth to ground water beneath Ciudad Juarez varies from about 100 to 250 ft, except near the Rio Grande where depths are often less than 70 ft.

- In heavily developed parts of the Hueco-Tularosa aquifer, drawdowns since 1940 are up to 150 ft. Pumping cones of depression in municipal wellfields are the focal points of drawdown. Most of the drawdowns near municipal wellfields vary between 50 and 100 ft. Focal points of drawdown are shown beneath El Paso and Ciudad Juarez.

- 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 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 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 Juarez 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 Juarez. 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. Mixing due to pumpage, leakage from mud interbeds and artesian confining beds, cascading waters along well casings and screens, lateral salt water encroachment, and potential upconing have started to degrade the freshwater zone.

• The Hueco-Tularosa aquifer is moderately susceptible to contamination. The Texas portion of the aquifer has a moderate ground-water pollution potential (DRASTIC index) that ranges mostly from 80 -109 for general, municipal, and industrial sources (Cross and Terry, 1991). The DRASTIC index is 110 - 124 along the slopes of the El Paso Valley, where older bolson material has been incised by the Rio Grande.

• Nitrate data collected between 1994 and 1995 indicate nitrate problems in some parts of El Paso County. A cluster of wells in the vicinity of the Old Mesa Well Field in southwestern El Paso County exceed the 10 mg/L NO_3-N drinking water standard. Many of the samples in El Paso County tested between 5 and 10 mg/L NO_3-N. All of the wells in Ciudad Juarez and immediate vicinity are less than 5 mg/L NO_3-N.

• In the Ciudad Juarez area, residential water supplies were tested in 1987 for possible contamination of ground water by sewage. Fecal coliform was used as an indicator parameter. Forty-two samples were obtained; 30 from tap water and 12 from raw ground water. Ninety-one percent of raw ground-water samples were fecal coliform positive. Sixty percent of tap water samples were fecal coliform positive. The percentage of positive bacteria detections in these samples suggested that ground water beneath Ciudad Juarez was contaminated by sewage.

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 55 miles 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 La Amargosa, 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 southeastern Hueco Bolson and bounding mountains and plateaus that are hydraulically connected to the bolson along ground-water divides are grouped as one aquifer, the southeastern Hueco aquifer.

• The thickness of the bolson fill of the southeastern Hueco aquifer decreases from as much as 8,500 ft 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.

• Transmissivity values in the Cretaceous strata and bolson fill north of the Rio Grande are all relatively low. Well yields do not exceed 200 gpm usually and most well yields are less than 50 gpm. Aquifer tests performed in wells screened or open in Cretaceous strata gave transmissivity values between 0.22 and 1.50 ft^2/day. Aquifer tests in wells completed in bolson silts and sands gave transmissivity estimates between 0.43 and 94 ft^2/day. Higher transmissivity values are characteristic of a higher percentage of sand and gravel in the basin. Lower transmissivity values are characteristic of mud-rich sediments deposited in lacustrine and playa environments. Aquifer tests in basin fill indicate relatively low transmissivity values, sufficient only for livestock and domestic use.

• 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-HCO_3 and Na-SO_4 along the Diablo Plateau to Na-SO_4-Cl beneath the floor of the basin. In Mexico, waters vary from Ca-Mg-HCO_3 beneath the Sierra de San Ignacio, Sierra de La Armagosa, and the Sierra de San Jose Del Prisco to Ca-Mg-SO_4-Cl waters beneath the basin floor. Typically these ground waters have TDS that vary between 1,000 and 3,500 TDS. 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.

• Bedrock units exposed in the southeastern Hueco aquifer are moderately susceptible to contamination. The Diablo Plateau has a moderate ground-water pollution potential (DRASTIC index) that ranges from 95 - 124 for agricultural sources. The DRASTIC index for general, municipal, and industrial sources is lower, ranging from 65 - 94.

• The southeastern Hueco Bolson has a higher DRASTIC index, ranging from 110 - 124 for agricultural sources and from 80 - 94 for general, municipal, and industrial sources. Some qualification of this ranking is required. Even though the potential for contaminants at land surface being carried with infiltrating precipitation to the saturated zone is possible along arroyos, the potential for contamination along areas of the basin floor that are not juxtaposed to arroyos is generally small. The relatively dry climate, specific retention of the soil, and intensity and distribution of rainfall does not provide adequate moisture for wetting fronts to reach the saturated zone except along arroyos.

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/Juarez 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/Juarez Valley.

• Water level contour maps prepared with data collected in 1973 - 74 and 1994 - 1995 illustrate losing stream, underflow, and baseflow conditions on different segments of the alluvial floodplain. The condition of losing stream is apparent along the Chamizal zone where drawdown cones from municipal well fields have reversed the hydraulic gradient between the river and the Rio Grande aquifer. Drawdowns have intensified along the Chamizal zone since 1973. Alluvial underflow predominates between the Chamizal zone and the El Paso/Hudspeth county line. Along this stretch of floodplain, ground-water flows subparallel to the direction of surface discharge, and head in the aquifer is approximately equal to the head in the river. The head elevation along this reach did not change significantly since 1973. The condition of baseflow prevails between county line and Fort Quitman. Flow is oriented subperpendicular to the direction of surface discharge and ground water clearly discharges to the Rio Grande. Hydraulic head in this part of the floodplain has increased since 1973.

- 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 groundwaters 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 TDS range. Total dissolved solids are higher in alluvial deposits in Hudspeth County, falling mostly within the 3,000 to 6,000 TDS 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 Juarez 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.

- Rio Grande waters are already contaminated above the El Paso/Ciudad Juarez metroplex. Contaminants include TDS, fecal coliforms, sulfates, and chlorides. Possible causes of these contaminants include irrigation return flows and municipal discharges. The quality of Rio Grande water deteriorates along the El Paso/Ciudad Juarez corridor and further downstream. Contamination is deduced by fecal bacteria as an indicator parameter. Immediately below El Paso, fecal coliforms as high as 290,500 colonies per 100 mL of water have been reported in Rio Grande water.

- The Rio Grande aquifer is highly susceptible to contamination. The aquifer can be contaminated rapidly by land application of fertilizers and pesticides, by leaching from septic tanks and feedlots, and by infiltration of chemicals or hazardous waste from storage facilities or from accidental spills. Consisting mostly of permeable unconsolidated deposits, the aquifer has received a DRASTIC index greater than 154 across much of the study area.

Diablo Plateau Aquifer

- The Diablo Plateau covers all but the southern part of Hudspeth County, Texas. The plateau is juxtaposed against regional grabens that formed by Quaternary-age lateral extension and normal faulting. The Campogrande fault displaces Cretaceous strata against bolson deposits southwest of the fault, forming an escarpment of more than 400 ft. Together with Otero Mesa to the north, the Diablo Plateau is a gently eastward-sloping structure situated at an elevation of between 4,400 and 5,200 ft. It is bounded by the Hueco-Tularosa Bolson on the southwest, by the Steeruwitz Hills, Carrizo Mountains, Van Horn Mountains, and Wylie Mountains on the south and southeast, and by the Salt Basin and Otero Break on the northeast. The edge of the Sacramento Mountains define the northern boundary of the aquifer.

- In Texas the Diablo Plateau consists of two rock units: (1) the Permian carbonate and evaporite rocks of Leonardian and Guadalupian age in northern Hudspeth County and, (2) the Cretaceous carbonate and clastic rocks of the Finlay, Cox, and Campogrande Formations, which outcrop roughly south of the Dell City parallel. The primary water-bearing units over much of the Diablo Plateau are Permian rocks with an average thickness of 1,300 ft. Ground water is encountered at depths from 200 ft to 1,500 ft. In the Dell City area the Permian aquifer is locally known as the Victorio Peak-Bone Spring aquifer. Lithologic control for this aquifer outside the Dell City area is extremely limited.

- In New Mexico, the plateau (known as the Otero Mesa) is composed almost entirely of Permian carbonate, clastic, and evaporite rocks of the Yeso, Victorio Peak, Bone Spring, and San Andres Formations. Of these, only the Victorio Peak and Bone Spring Formations comprise the main aquifer.

- Aquifer tests conducted in the Diablo Plateau aquifer suggest that permeabilities in the aquifer are solution-and-fracture controlled. Video logs run in several test holes revealed continuous vertical fractures and grapefruit-size dissolution cavities. Approximately 44 percent of wells drilled in the Dell City area are prolific; many wells produce 100 gpm or less, even when drilled near wells successfully pumping 2,000 gpm. This response is an artifact of the high transmissivity contrast which characterizes the Permian and Cretaceous carbonate rocks in the Diablo Plateau region.

- The potentiometric map for the Diablo Plateau aquifer and surrounding region indicates that groundwater flow is generally from southwest to northeast beneath the Diablo Plateau and from northwest to southeast beneath Otero Mesa. Flow from both regions converges towards Dell City and the Salt Basin along flowpaths with average hydraulic gradients of 0.0004, although gradients are as steep as 0.001. The Dell City area is encompassed by a shallow, broad cone of depression in the potentiometric surface that has formed as a result of extensive irrigation and groundwater development. A “trough” runs beneath the Sacramento River towards Dell City, its widely spaced contour lines suggesting high transmissivity along the trough. The potentiometric surface is near land surface in the Salt Basin where ground water discharges by evaporation.

- The ground-water resources in the study region are mostly undeveloped, except in the Dell City irrigation district. Hydrographs of six wells in the Dell City area show significant changes in water levels since predevelopment. The rest of the system is almost at steady state. As pumping exceeded recharge, water levels dropped constantly until the mid-1980's at an average rate of 1.3 ft/year, totaling 25 to 45 ft of drop areawide. Since then, irrigation pumpage diminished, and water levels have risen slightly.

- Tritium and carbon-14 (^{14}C) levels measured in wells on the Diablo Plateau indicate that most of the ground water samples contain recent water (i.e., water recharged within the last 50 years). The tritium and ^{14}C values display significant changes within short distances and no clear distribution pattern, thus emphasizing the practical importance of fracture and karstic flow. Recharge occurs over the entire plateau (approximately 2,900 mi^2) as demonstrated by the areal distribution of tritium-rich samples. Most recharge probably takes place during flooding of the ephemeral creeks ("arroyos") that cross the plateau.

- Ground water in the Diablo Plateau aquifer is fresh to brackish, with total dissolved solids (TDS) concentrations as low as 500 mg/L in the Sacramento River area, to over 3,800 mg/L in central-western Otero Mesa where water-bearing strata are interbedded with the gypsiferous Yeso Formation. In the Dell City area, where return flow from irrigation leaches salts from the soils and evaporates, TDS concentrations reach 6,500 mg/L. Hydrochemical facies in the area vary from $Na\text{-}Ca\text{-}HCO_3$ and $Na\text{-}SO_4$ in the southwest to $Na\text{-}SO_4$, $Ca\text{-}SO_4$, and Na-Cl in the north and northeast. The change in chemistry from southwest to north/northeast can be attributed to the changing lithology from Cretaceous carbonates to evaporate-rich Permian rocks along flowpaths, and to ground-water evaporation and mixing.

- The Diablo Plateau aquifer is moderately susceptible to contamination. The Diablo Plateau has a moderate ground-water pollution potential (DRASTIC index) that ranges from 95 - 124 for agricultural sources, the principal activity in the region. The DRASTIC index for general, municipal, and industrial sources ranges from 80 - 124.

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CHAPTER 1 - INTRODUCTION

Preface

Purpose

At the request of the U.S. Environmental Protection Agency (USEPA), the Texas Water Development Board (TWDB) and the New Mexico Water Resources Research Institute (NMWRRI) undertook this study to characterize binational aquifers in parts of far west Texas, south central New Mexico, and northeastern Chihuahua, Mexico. The study area lies along a corridor centered at the City of El Paso\Ciudad Juarez metroplex and extending 62 mi (100 km) on either side of the international border. The study uses well-established hydrogeological, hydrochemical and numerical modeling techniques to trace ground-water flowpaths, to assess regional water quality, and to define aquifer recharge and discharge areas and areas susceptible to contamination.

Many of the surface and ground-water resources along the transboundary corridor are shared between the two nations, yet little binational study of these resources has been undertaken. A number of environmental and hydrologic problems have been identified that will require the cooperation of both nations to solve. Solutions to water-related problems can be derived only when a better understanding of transboundary water resources is attained. This study is an important step toward attaining a better understanding of these binational resources.

To complete this study, data from several sources had to be combined into one data base. GIS coverages of ground water, surface water, and land use attributes were developed from the new data base. This report provides results of the study. Appendix C provides documentation of GIS coverages.

Participating agencies

Key participants in the project included the TWDB and the NMWRRI. TWDB team-members included Barry Hibbs, principal hydrogeologist and co-project manager; John Ashworth, geologist and co-project manager; Radu Boghici, assistant hydrogeologist; Mark Hayes, Erika Boghici, and Darrell Peckham, GIS analysts; Steve Moore and Frank Bilberry, engineering technicians; and Jay Galvan, Steve Gifford and Mike McCathern, layout and cartography. NMWRRI team-members included Bobby Creel, project manager; Adrian Hanson, environmental engineer; Zohrab Samani, hydrogeologist; John Kennedy, GIS analyst/geologist; and Pamela Hann and Kenny Stevens, research assistants. Several technical and support staff from the Texas Water Development Board, New Mexico Water Resources Research Institute, and New Mexico State University made ancillary contributions.

Assessments of the Mesilla Bolson aquifer, Jornada del Muerto Bolson aquifer, and Rio Grande aquifer (Leasburg Dam to the El Paso narrows) were performed by the New Mexico team. Assessments of the Hueco-Tularosa aquifer, southeastern Hueco aquifer, Diablo Plateau aquifer, and Rio Grande aquifer (El Paso narrows to Indian Hot Springs) were performed by the Texas team. Collation of regional GIS coverages from the Texas and New Mexico teams and report assembly and publication were performed by the Texas Water Development Board.

The Comision Nacional Del Agua (CNA), Mexico, and Junta Municipal de Agua y Saneamiento (JMAS) de Ciudad Juarez, provided hydrologic data and technical assistance. Logistics of international data transfers were facilitated by the U.S. and Mexican sections of the International Boundary and Water Commission (respectively, IBWC and Comision Internacional de Limites y Aguas, [CILA]).

Acknowledgments and disclaimer

Research supported by the U.S. Environmental Protection Agency under USEPA contract numbers X 996343-01-0 and X 996350-01-0. The views and conclusions in this report are those of the TWDB and NMWRRI and should not be interpreted as necessarily representing the official opinions of the USEPA, IBWC, CILA, CNA, or JMAS.

Adjunct research institutions and public agencies are credited for providing technical and administrative assistance for this study. These include the University of Texas Bureau of Economic Geology (BEG); the Center for Environmental Research Management (CERM) at the University of Texas at El Paso (UTEP); the IBWC and CILA; the U.S. Geological Survey (USGS), New Mexico State District Office, Albuquerque; the Public Services Board (PSB), City of El Paso; the JMAS, Ciudad Juarez; the Texas Natural Resource Conservation Commission (TNRCC); the Texas Natural Resources Information System (TNRIS); and the New Mexico Environment Department (NMED). Several individuals are acknowledged for providing technical and administrative assistance and data. They include Chris King of the USEPA; Bruce Darling of LBG Guyton Associates; Jim Mayer of Georgia Southern University; Edward Collins and William Mullican of BEG; Nancy Lowery of CERM; Sylvia Waggoner, Cruz Ito, Rong Kuo, Carlos Pena, Jim Robinson, and Jose Valdez of IBWC; Antonio Rascon of CILA; Mike Kernodle, Brennon Orr, and Linda Beal of the USGS; Ernest Rebuck; Sayeed Joraat, and Roger Sperka of El Paso PSB; Francisco Nunez of Ciudad Juarez JMAS; and Miguel Pavon of TNRIS.

Regional Geographic Setting

Location

The area encompassed by this study lies between north latitudes 33 24' 32" and 30 30' 00" and west longitudes 107 18' 18" and 104 50' 31". The study area includes all of Doña Ana and Otero Counties, New Mexico and all of El Paso and Hudspeth Counties, Texas. Part of northeastern Chihuahua, Mexico is included in the study area (Figure 1.1). Total land surface area encompassed by the study is about 24,900 mi^2, of which nearly 8,800 mi^2 is in Mexico. Principal transboundary aquifers in the region include the Hueco-Tularosa aquifer and the Mesilla Bolson aquifer (Figure 1.2). These aquifers are extensively developed and satisfy most of the municipal and industrial water demands in the City of Las Cruces, City of El Paso, and Ciudad Juarez. Other aquifers include the southeastern Hueco aquifer, the Diablo Plateau aquifer, the Rio Grande aquifer, and the Jornada del Muerto aquifer (Figure 1.2). Of the latter, only the Rio Grande aquifer is extensively developed and transboundary in extent.

Topography and drainage

The study area lies primarily within the southeastern segment of the physiographic Basin and Range Province. The topography is dominated by long, narrow mountain ranges, intermontane basins (flats and draws), and gently sloping plateaus (Figure 1.3). The most prominent topographic feature in the New Mexico part of the study area is the Sacramento Mountains in Otero County. The highest peak in the Sacramento Mountains is Sierra Blanca at 12,003 ft above sea level. The Organ Mountains of Doña Ana County reach a peak elevation of 9,012 ft. The Franklin Mountains of El Paso County, Texas, and the Eagle Mountains of Hudspeth County, Texas, attain respective elevations of 7,192 and 7,484 ft. The Sierra de Las Vacas, the highest topographic mountain range in the Mexican part of the study area, reach a peak elevation of 7,218 ft.

Surface drainage for the Sacramento Mountains and Otero Mesa is to the Tularosa Basin and Salt Basin, two internal drainage, closed basins (Figures 1.3 and 1.4). Surface drainage for the U.S. parts of the Mesilla and Hueco Basins is mostly captured by the Rio Grande, the principal surface drainage in the study area. The Mexican portion of the Hueco Basin is also drained by the Rio Grande. The Mesilla Basin (referred to as Bolson de Mesilla - Samalayuca in Mexico [de La O Carreno, 1957]) is drained partly by the Rio Grande and partly by Laguna Coyames in Mexico. The Diablo Plateau drains mostly into the Salt Basin to the east and

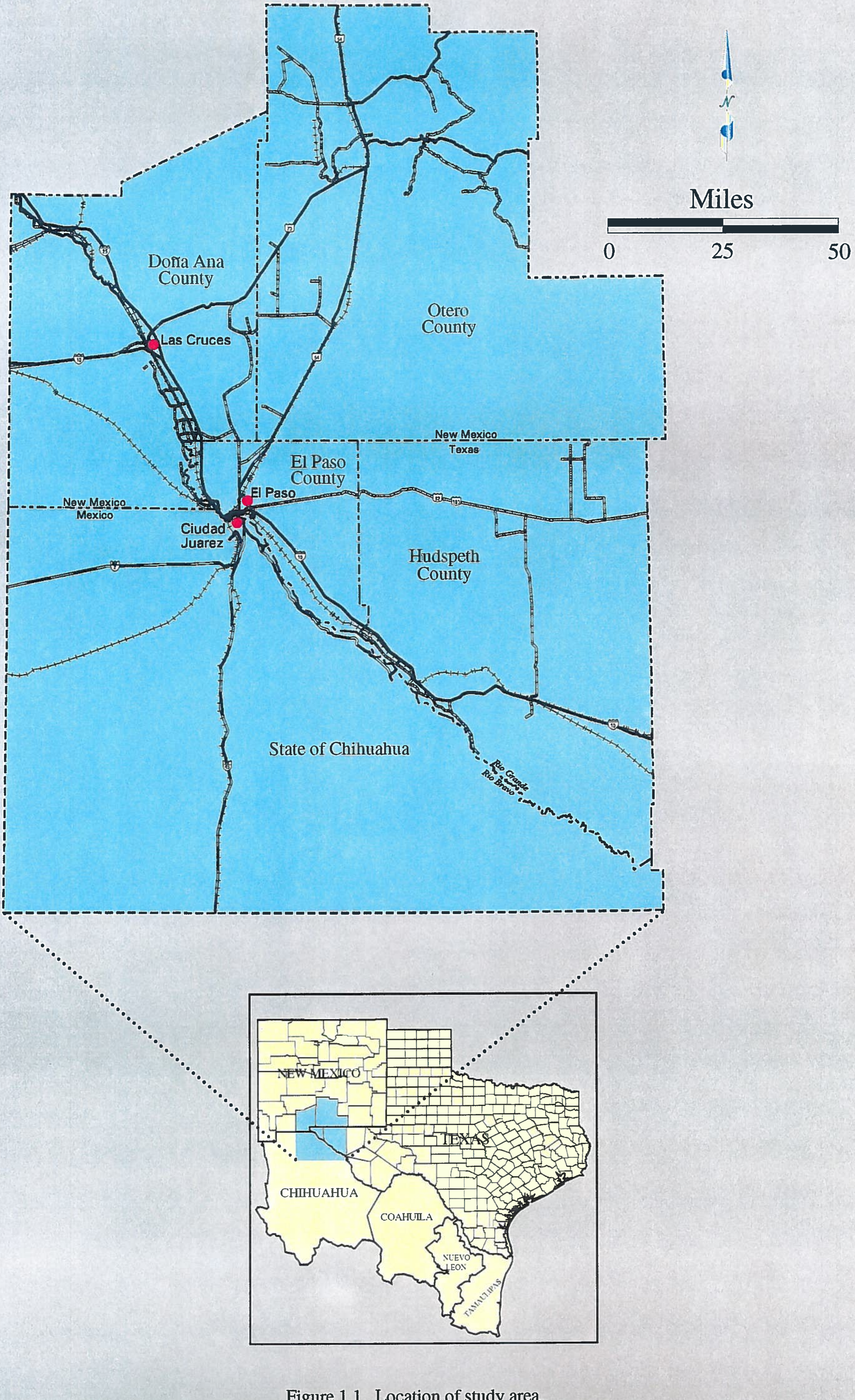
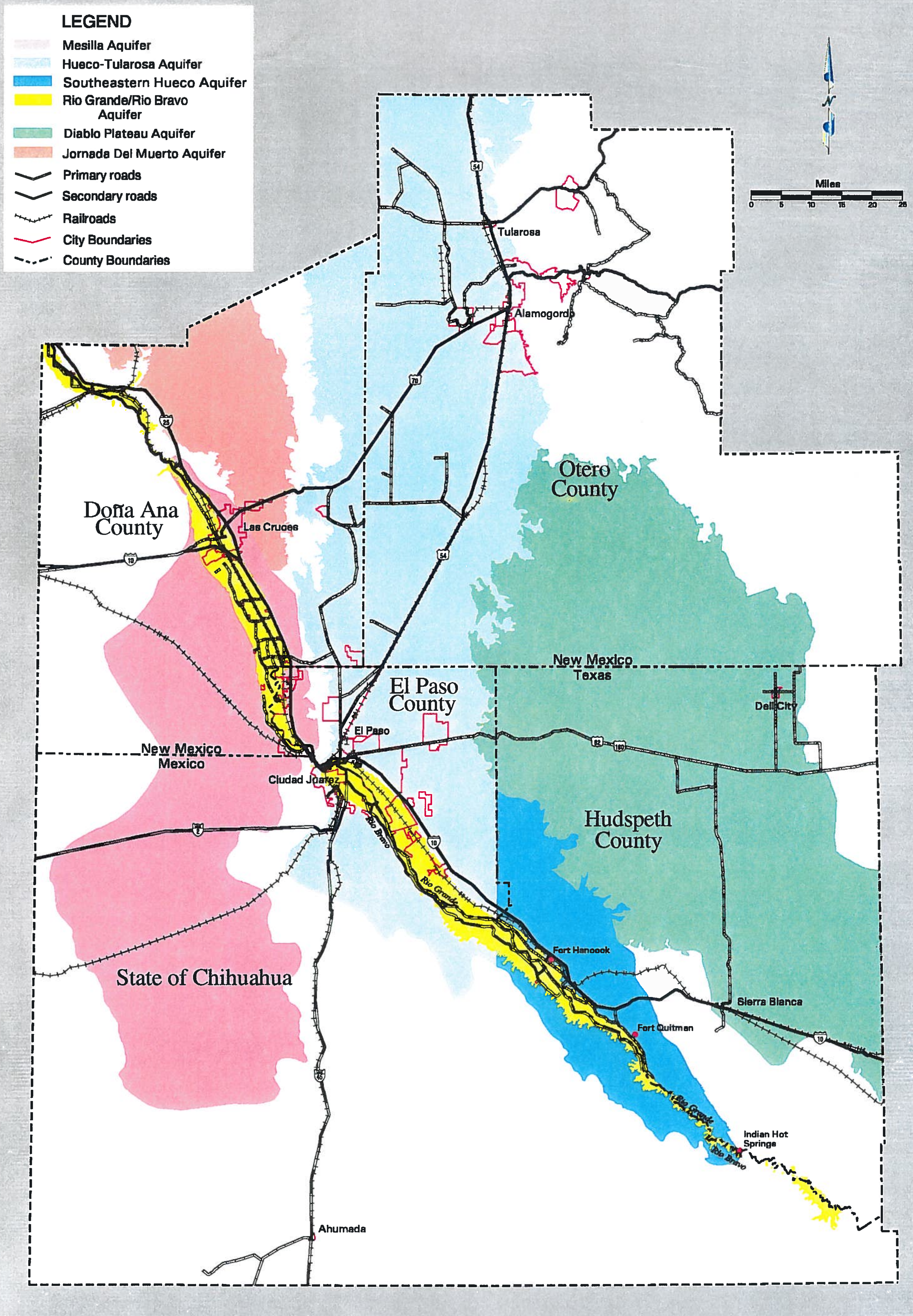


Figure 1.1. Location of study area.



1.2. Transboundary aquifers in the study area.

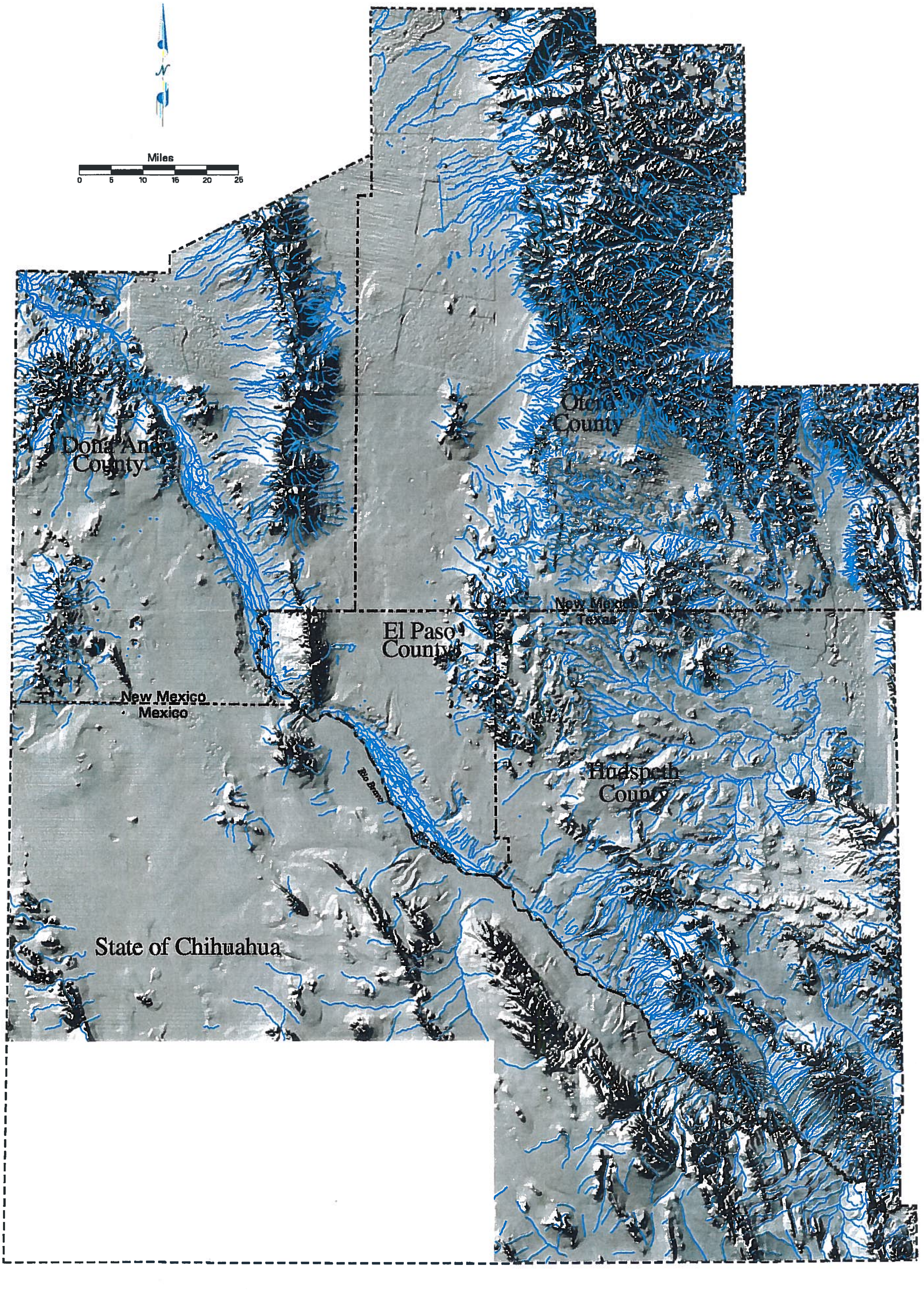


Figure 1.3. Three –dimensional depiction of surface topography and principal drainage in the transboundary study area.

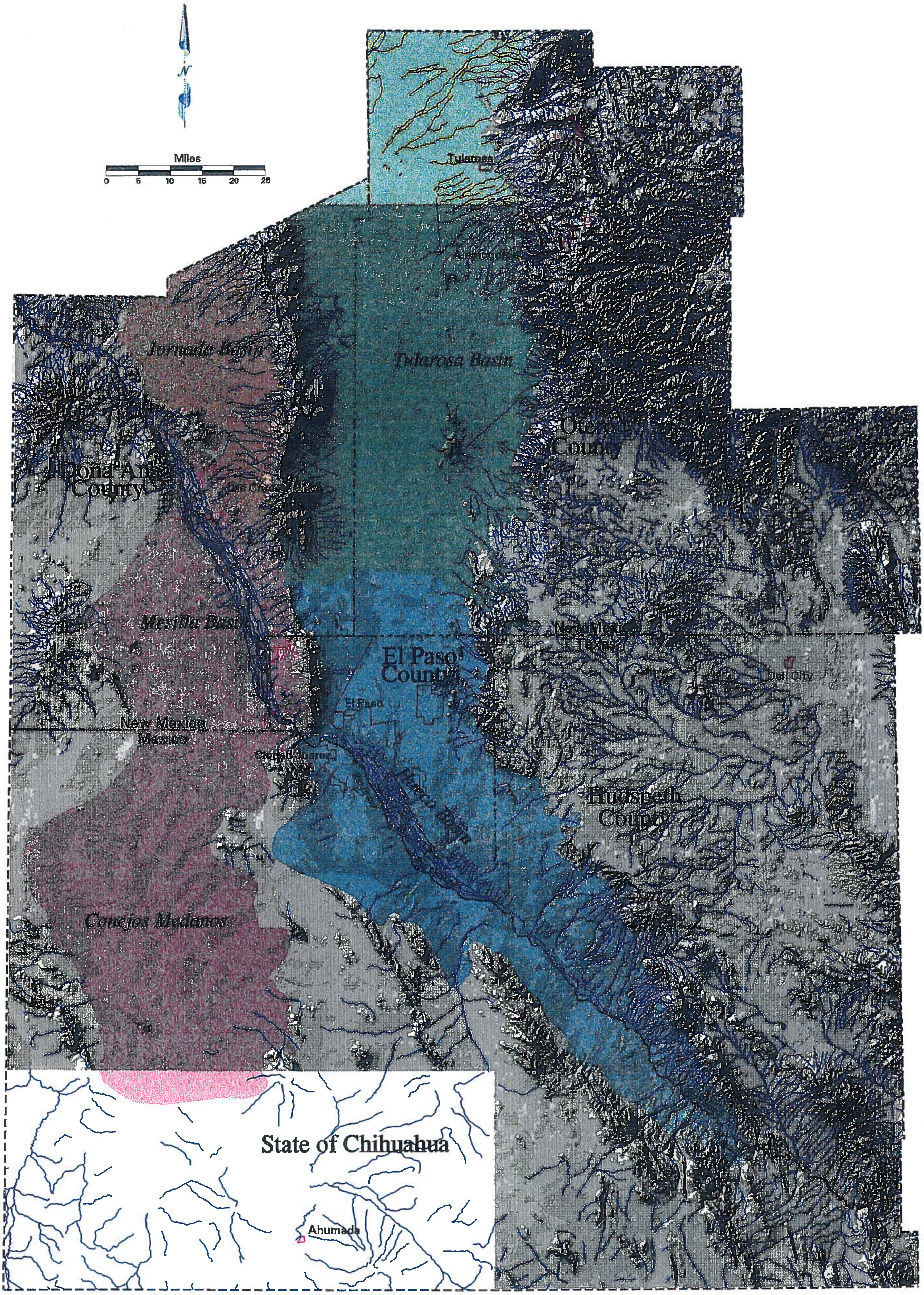


Figure 1.4. Surface drainage basins in the study area. These are defined by surface drainage characteristics and not by intrabasin and interbasin ground-water flow.

partly to the Rio Grande to the south along a drainage divide (Figure 1.3).

Climate

The study area is typical of the arid southwest, with mostly clear skies and limited rainfall and humidity. Average annual precipitation varies from as little as 6 in/yr in low lying basins to as much as 30 in/yr in the pine covered pinnacles in the Sacramento Mountains (USBR, 1984). Average annual rainfall over most of the study area is less than 12 in/yr.

Climatological data have been collected for decades at and near the major metropolitan areas. The climate at Las Cruces is arid in low-lying areas and semiarid in mountainous region. Average annual precipitation at Las Cruces, mostly in the form of rain, is 8.39 in (Frenzel and others, 1992). Nearly one-half of precipitation is from thunderstorms that occur from July through September. Large diurnal changes in temperature up to 30°F are common, especially during the summer months (Frenzel and others, 1992). Mean annual temperature is 60°F in Las Cruces.

The climate is arid to semiarid in the El Paso/Ciudad Juarez area (IBWC, 1989). Precipitation is mostly from thunderstorms that occur sporadically during the summer months. Precipitation records at several meteorological stations indicate that average annual rainfall along the El Paso/Ciudad Juarez corridor is about 10 in (IBWC, 1989). Temperatures during the summer may reach 100°F for several days. Normal night time temperatures during the summer vary from high 60°F to mid 70°F. Winter temperatures occasionally are below freezing and usually range from 40°F to 60°F (IBWC, 1989).

Toward the eastern part of the study area, near the City of Sierra Blanca, Texas, the subtropical-arid climate is characterized by high mean temperatures with large daily and annual fluctuations, and low mean precipitation with widely separated annual extremes (Larkin and Bomar, 1983). Average annual low temperatures are nearly 48°F and average high temperatures are close to 80°F (Larkin and Bomar, 1983). Precipitation is mostly in the form of local and irregular summer showers (Nativ and Riggio, 1990). Winter rainfall accounts for less than one-third of total precipitation (Larkin and Bomar, 1983). Mean annual precipitation in Sierra Blanca is 12 inches.

Population and economy

The population of Doña Ana County was estimated to be 155,469 in 1994 up from the 1990 census of 135,510 (USDC, 1995 and 1991). This was an increase of 14.73%. The increase between 1980 and 1990 was 40.66%. The 1990 census indicates that there were 49,148 households in Doña Ana County with an average of 2.95 persons per household. Aside from the household figures for Las Cruces (22,509), Hatch (411), Mesilla (715), and Sunland Park (2,963), the unincorporated areas had a total of 22,550 households.

The economy of Doña Ana County is largely dependent upon government jobs. In 1988, state and local government work provided 11,100 jobs and $167.4 million for county residents (USDC, 1990). This was the single largest category of earnings for the county, followed by private services with 10,900 jobs and $119.2 million. Federal work provided 4300 jobs and $105.1 million for the county in the same year. By 2020, the county earnings through private services are expected to reach $277.0 million per year for 17,600 jobs and should represent the largest source of income for Doña Ana County (USDC, 1990). State and local government work should provide $270.6 million through 12,700 jobs.

Doña Ana County has traditionally been an important producer of agricultural goods. In 1988 $18.8 million was earned in Doña Ana County through its farms. This constituted one of the largest segments of income for the county (USDC, 1990).

Otero County, had a population of 54,307 in 1994. The largest municipality is Alamogordo, which had a 1994 population of 29,628. The economy of Otero County before 1940 was based primarily on crop agriculture, livestock, and some mining (USBR, 1984). The population at that time was about 10,000. Isolated and flat areas in the Tularosa Basin were selected by the military in the early 1940's as sites for explosive and missile testing and the population grew to its present number mostly to support military infrastructure. Sand, gravel, and building stone provide the only substantial mining base.

The City of El Paso is the largest city in El Paso County, Texas. Census information compiled in 1995 indicated that 583,431 people lived in the City of El Paso, or 87% of the county total (668,358). Fort Bliss (14,202) and smaller cities and rural areas accounted for the remaining county population of 84,927. Colonias populations are estimated to total 72,754 in El Paso County (TWDB, 1995).

El Paso is an important center of commerce and industry. Industries include smelting and metal refineries, gasoline refineries, meat packing and food processing facilities, and light manufacturing. Military installations in and adjacent to El Paso provide a substantial economic base. Rural areas, especially in the El Paso/Juarez Valley, host a number of agricultural industries, including irrigated agriculture, livestock, poultry, and dairy production.

Hudspeth County is the most rural county in the U.S. part of the study area. Total population in Hudspeth County was 3,422 in 1995. The largest cities in 1995 were Fort Hancock (1,993), Sierra Blanca (700), and Dell City (779). Irrigated agriculture is the principal activity in the Dell City and Fort Hancock areas. Dell City uses ground water for irrigation and Fort Hancock uses Rio Grande water mostly, and some ground water. The economy of Sierra Blanca is sustained by the ranching industry, interstate travel, and interstate sludge disposal facility. Rural areas not adjacent to these cities are almost entirely ranching operations, except near the Rio Grande, where irrigated agriculture is common.

The population of Ciudad Juarez, northeastern Chihuahua Mexico was 850,000 in 1990 (USEPA, 1996). The population grew to 1,010,000 in 1995 (USEPA, 1996). We could not determine the number of residents in rural parts of the Mexican study area, but place the number at fewer than 50,000. Principal industries in Ciudad Juarez include industrial manufacturing, services, and tourism. Irrigated agriculture is common along the Rio Grande. Ranching operations are the principal activities in rural areas at distances from the river.

History of ground-water development

Mesilla Basin ground water has been a source of water for agriculture, municipal and industrial use since the early settlement in the area. Prior to 1950, non-agricultural withdrawals were negligible. It is estimated that non-agricultural ground-water withdrawals have increased from about 6 $ft^3/_s$ in 1950 (Frenzel and others, 1992) to upwards of 60 $ft^3/_s$ in the late 1980's (NMSEO, 1992). Ground water pumping for agriculture as a supplemental source of irrigation water constitutes a large volume of extraction from the Mesilla Basin. In the late 1940's, there were approximately 70 irrigation wells in both the Rincon and Mesilla Valleys combined. During the drought of 1951 - 57, several hundred wells were drilled in the Mesilla Valley. Many wells were also drilled during the shortage of surface water from 1963 to 1966. As of 1975 there were about 920 useable irrigation wells in the Mesilla Valley (Frenzel and others, 1992) most of which were drilled and completed in the floodplain alluvium.

The number of irrigated acres in the Mesilla Valley increased from about 25,000 acres near the turn of the century to about 77,000 acres during 1940 - 1975 which is about two-thirds of the area of the valley. In the Mesilla Valley after 1975, a large number of deep wells were drilled through the alluvium and completed in the Mesilla Bolson deposits in order to obtain higher quality water than that available from shallow wells. The City of Las Cruces is currently pumping about 17,000 - 18,000 acre-ft of water per year for municipal use.

The first water supply wells in the City of El Paso/Ciudad Juarez area probably were dug by early Spanish missionaries. These shallow wells were used to augment surface water supplies, especially during droughty periods when there was little or no streamflow in the Rio Grande (White, 1987). The first municipal water supply well for the City of El Paso was dug in 1892 (Sayre and Livingston, 1945). Subsequently other wells were installed and by 1918 the City of El Paso had about 150 wells screened in the Hueco Bolson (IBWC, 1989). Presently there are 142 city wells screened in Hueco Bolson sands and gravels. Hundreds of shallow irrigation wells have been drilled in the El Paso Valley, but many are active only during prolonged droughty spells. Estimates of the number of irrigation wells are not available because well inventories have not been conducted in sufficient detail to make accurate estimates.

Ciudad Juarez drilled its first water supply well in 1925 (IBWC, 1989). The number of wells drilled by the city peaked in the 1950's when there was a prolonged shortage of surface flows in the Rio Grande. Today, Ciudad Juarez maintains about 170 operational water wells; 100 or so of these are normally active. The drilling of an irrigation well is recorded in 1935 in Juarez Valley (de la O'Carreno, 1957), and by 1949 over 100 irrigation wells had been installed (IBWC, 1989). The number of irrigation wells in and adjacent to the Juarez Valley totaled 1,120 in 1980 (IBWC, 1989). Some of these draw water from deeper Hueco Bolson sands and gravels, although several are screened in the Rio Grande alluvium.

Regional Geologic Setting

Geologic characteristics

The southeastern Basin and Range province is defined by topographically high mountain ranges and plateaus separated by normal faults from adjacent basins. Geologic units in the study area range from Precambrian to recent (Figure 1.5). The ages of strata in outcrop are primarily Precambrian, Cretaceous, and Tertiary in mountainous areas, Cretaceous and Permian in plateaus, and Tertiary and Quaternary in bolson areas.

Major geologic features in the area formed in response to the Rio Grande rift, a fault bounded structural feature with uplifted blocks on the east/southeast and west/southwest. Uplifted blocks sometimes rise a few thousand feet above valley floors due to vertical displacement along normal faults. Many of the complex grabens have subsidiary grabens within the main basin (Wilkins, 1986; Collins and Raney, 1991). The basins are asymmetrical and structural relief, in general, is greater on the west and southwest sides of the basins (Chapin, 1971).

Basin fill of Cenozoic age was derived from erosion of rocks from flanking highlands, interbedded in some places with volcanic flows and tuffs. Basins include, from northwest to southeast, the Mesilla Basin, Tularosa Basin, and Hueco Basin (Figure 1.4). The Mesilla and Hueco Basins are "open" basins, and surface runoff in these basins is drained by the Rio Grande. The Tularosa Basin is a "closed" basin, having no exterior surface drainage. Open and closed basins are phrases sometimes used to describe interbasin ground-water flow, or lack thereof, to other basins or through-flowing streams in the basin-and-range province. The conventions used by Eakin and others (1976) are used in this report to describe ground-water flow (Figure 1.6). According to their convention (Eakin and others, 1976), the Mesilla and Hueco Basins are "regional sinks" and the Tularosa Basin is a "partly drained" basin (Figure 1.6). "Open" and "closed" basins are used hereafter to describe surface runoff and surface drainage in basins (Figure 1.4), not ground-water flow.

Consolidated rock types are important to the makeup of the hydrostratigraphy of the study area. These include, from oldest to youngest, Precambrian metamorphic rocks that are weakly fractured; Paleozoic (especially Permian) carbonate and clastic rocks that are fractured and sometimes intensely karstified; Mesozoic (mostly Cretaceous) rocks that are fractured and occasionally karstified; and Tertiary and Quaternary volcanic intrusive and extrusive rocks that are usually fractured and jointed.

Semi-consolidated to unconsolidated sediments include Cenozoic basin fill, Quaternary Rio Grande alluvium, and recent alluvial deposits not associated with the Rio Grande (Figure 1.5). The Cenozoic basin-fill sediments consist largely of sand and gravel lenses interstratified with silt and clay. Significant amounts of interbedded volcanics are shown in some geologic logs, especially in the lower basin fill. Depositional environments included alluvial fans, riverine systems, and ephemeral lakes and saline playas. Vertical offset by Basin and Range faults and tabular and lenticular geometries of sand, silt, and clay deposits create significant intrastratigraphic discontinuities.

The Rio Grande alluvial deposits form 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 (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. Recent alluvial deposits not formed by the Rio Grande are associated with arroyos that drain the mountains and flanking plateaus. Typically these deposits are poorly sorted sands, silts, and gravels.

Geologic history

During much of the Paleozoic Era, the study area was covered over large areas by shallow seas (Wilkins, 1986). Carbonate and clastic rocks were deposited in and adjacent to the seas, especially during the Permian Period (Henry, 1979). Seas had regressed by the Triassic and Jurassic Periods and weathering and erosion of continental rock masses formed extensive red beds in northern parts of the Rio Grande rift. Triassic and Jurassic rocks were eroded or were not deposited prior to formation of Cretaceous rocks in the southern part of the rift.

Seas had transgressed by the Cretaceous Period and marine environments were the sites of deposition of thick sequences of limestone and clastic sediments (Henry, 1979; Wilkins, 1986). These and older rocks were deformed during the Late Cretaceous, Early Tertiary Laramide orogeny. Major thrust faults developed along the southeastern edge of the study area as a result of the orogeny, and deformation produced a series of north-northwest trending folds (Henry, 1979). Andesite intrusions and volcanic flow associated with Laramide faulting and volcanic activity continued through the Oligocene (Wilkins, 1986).

Rifting began at least 18 million years ago and took place along a north-northwest structural trend (Wilkins, 1986). The region was uplifted from elevations near sea level to several thousand feet above sea level during the late Tertiary. Block-faulting was superimposed on Laramide fault and fold structure, and thick sequences of bolson fill were deposited as a result of block faulting and uplift. Extension, along with uplift and erosion of flanking highlands formed the graben-type basins. Normal fault movement continues to the present in some parts of the study area (Belcher and Goetz, 1977).

The ancestral Rio Grande became a through-flowing river in the study area during the late Pliocene to early Pleistocene (Gustavson, 1990). Incision of the Rio Grande was affected by integration of the Upper Rio

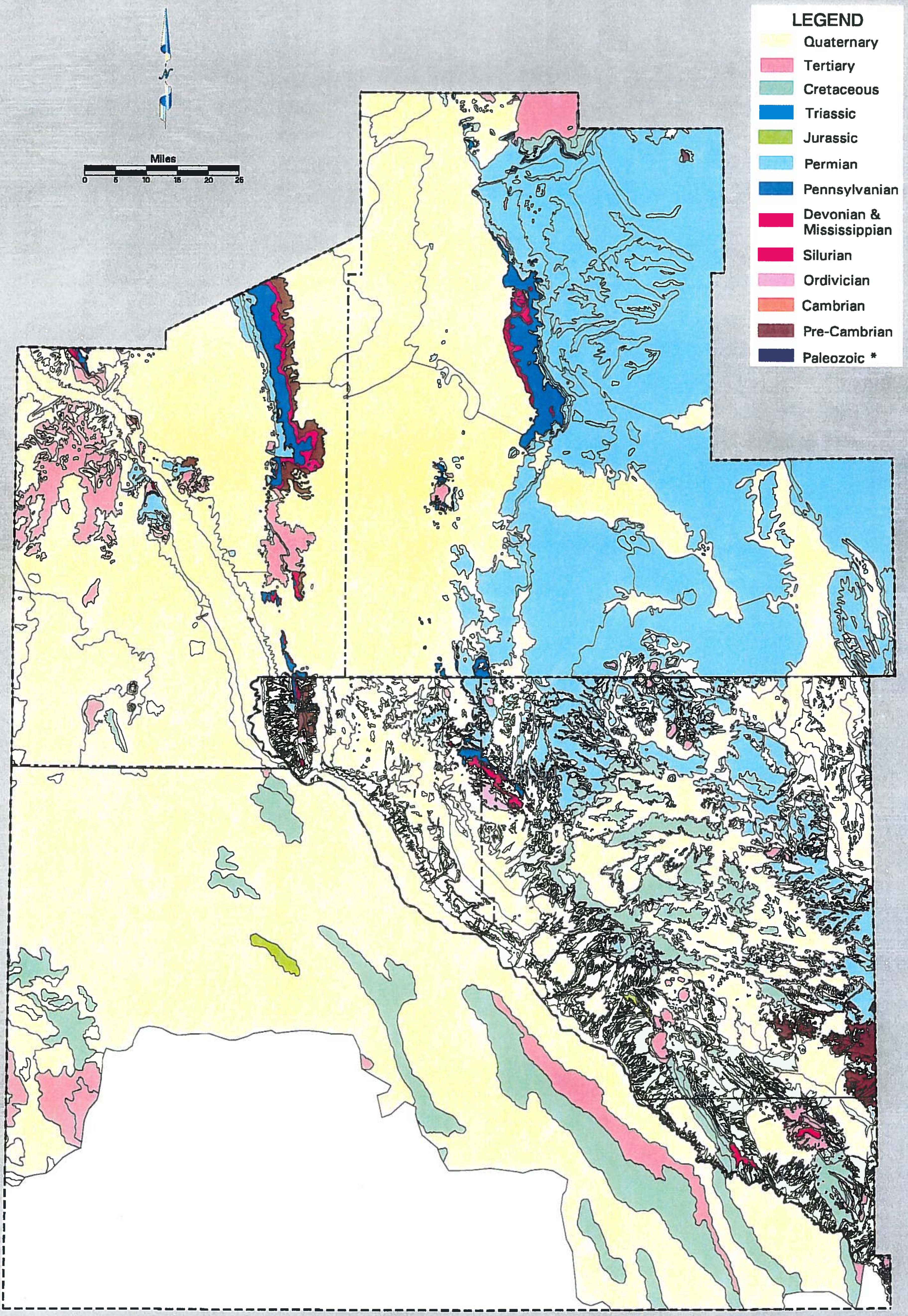


Figure 1.5. Geologic coverage map of the regional study area (source, Texas Bureau of Economic Geologic atlas sheets; Instituto Nacional de Estadistica, Geografia e Informatica geology sheets; New Mexico Geological Society highway geologic map).

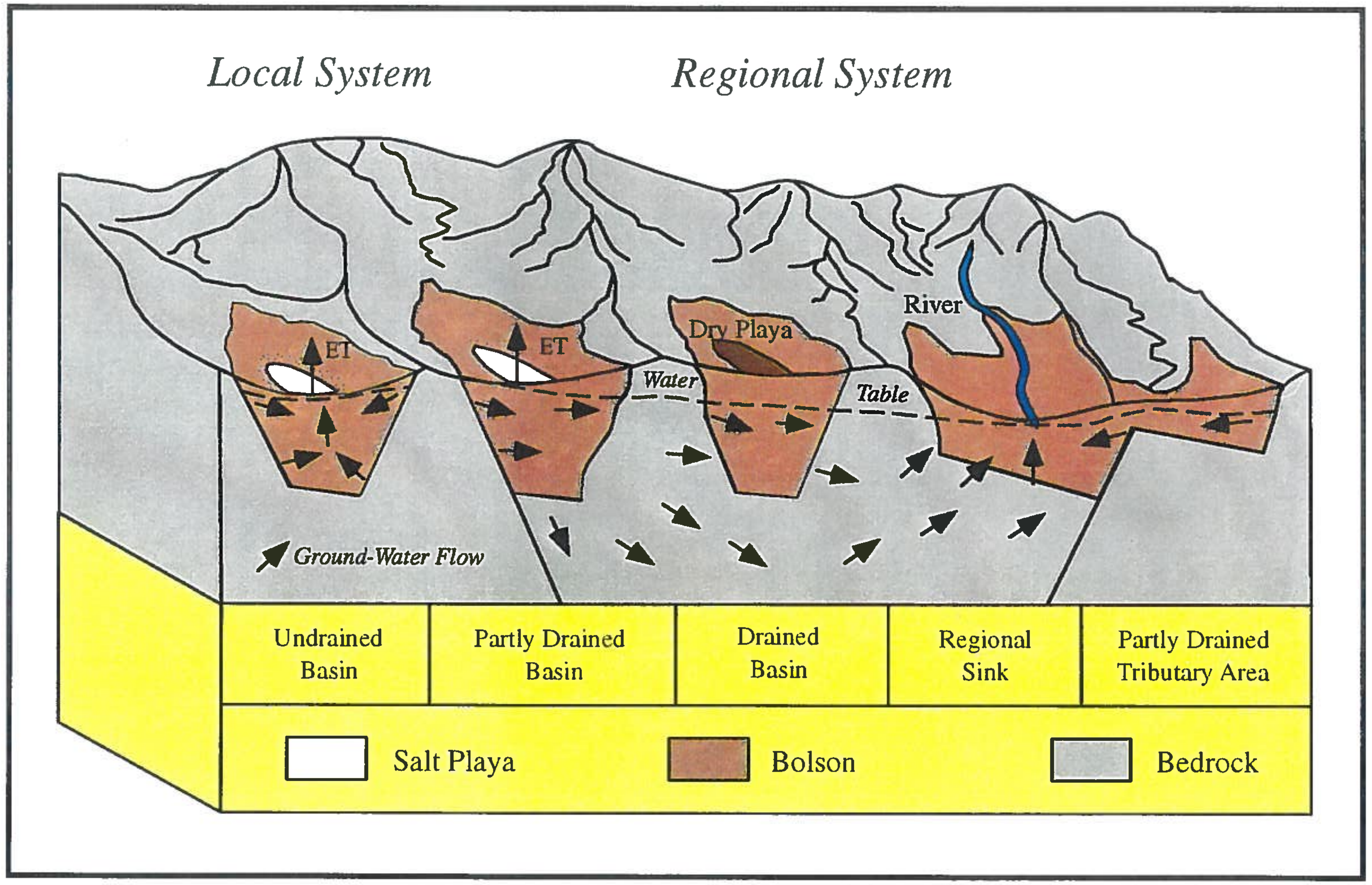


Figure 1.6. Conceptual hydrogeologic model showing undrained basins, partly drained basins, drained basins, and regional sinks (modified from Eakin and others, 1976).

Grande system with the lower Rio Grande system and drainage into the Gulf of Mexico. Basins in the study area display arroyo dissection of basin fill that developed in response to new base level of the Rio Grande.

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CHAPTER 2 - MESILLA BASIN GROUNDWATER AQUIFER SYSTEM

This section will describe three groundwater aquifers within the Mesilla basin groundwater aquifer system. These are the Mesilla Bolson, the Rio Grande Floodplain Alluvium, and the Jornada del Muerto Bolson. These are shown in the western edge of the study area in Figure 1.2. These three groundwater aquifers are connected hydrologically, however the connections are restricted by aquitards and/or faults and therefore are considered and described as separate aquifers. The discussion of these groundwater systems (Mesilla basin aquifers) first includes general information of location, extent of the aquifers, climate, development, and use of the resource followed by sections specific to each of the aquifers such as regional structure, depositional history, geology, water bearing characteristics, quality, recharge and discharge.

Location and Extent

The Mesilla basin aquifer system is an extensive intermontane aquifer system which extends from southern New Mexico to northern Mexico. It is surrounded by mountains which form the boundaries of the aquifers. The eastern boundary consists of the San Andres Mountains, San Augustin Mountains, Organ Mountains, Bishop Cap and the Franklin Mountains. The East and West Potrillo Mountains, Aden Hills and Sleeping Lady Hills are on the west. On the north, there are Robledo Mountains and Doña Ana Mountains. On the southeast are the Sierra de Cristo Rey at the international boundary and the Sierra de Juarez just north of the international boundary. The Rio Grande enters the basin through Selden Canyon between the Robledo Mountains and Doña Ana Mountains. From Selden Canyon the river traverses the Mesilla basin diagonally for approximately 60 miles until it exits into the Hueco Bolson through the El Paso narrows between the Franklin Mountains and the Sierra de Cristo Rey. The Rio Grande floodplain and lands adjacent to the floodplain define the Mesilla Valley which is a low gradient, narrow, alluvial valley ranging in width from a few hundred feet to about 5 miles near Las Cruces. Altitude of the valley varies from 3,980 feet at Leasburg Dam in Seldon Canyon to 3,729 feet at the El Paso narrows.

Steep bluffs rise up from the Mesilla Valley floor, and form the walls of the valley. To the west of the Valley the bluffs immediately level off and form the broad piedmont slope that extends for over 20 miles until it intersects the mountain fronts. This broad mesa is known as the West Mesa, and it encompasses approximately 750 square miles. The Jornada del Muerto is another broad mesa on the east side of the Mesilla Valley that extends 100 miles north from Las Cruces to San Marcial. To the east and south of the Valley, the bluffs level off slightly and quickly meet the base of the San Andres Mountains, Organ and Franklin Mountains. The Mesilla Valley is located on the eastern side of the Mesilla basin and is characterized by a broad erosional surface of low topographic relief produced by the meandering Rio Grande. An extensive remnant of an earlier basin-floor surface, the "West Mesa" of recent water resource publications (Wilson and others, 1981; Myers and Orr, 1985), that predates river-valley incision is preserved between the Mesilla Valley and the East Potrillo and Robledo mountain uplifts to the west.

The surface water system is comprised of the Rio Grande and its tributaries and a network of canals, laterals and drainage ditches that discharge to the river. The Rio Grande, which is the main surface-water feature associated with the Mesilla Valley, is the primary source of irrigation water in the Mesilla Valley. The Rio Grande is a highly regulated stream with reservoir storage and channel stabilization throughout the area. The operation of the river is controlled by an irrigation project (Rio Grande Project), interstate compact, and international treaty. Operation of the Rio Grande is based on discharge at upstream index stations and storage in upstream reservoirs (Nickerson and Myers, 1993). The water is administered by the Elephant Butte Irrigation District (EBID) and El Paso County Water Improvement District #1 (EPCWID). To control water flow, surface water for the area is stored in two large reservoirs, Caballo Reservoir and Elephant Butte Reservoir. Elephant Butte Reservoir is about 75 miles upstream from Leasburg Dam, and Caballo Reservoir is about 45 miles upstream from Leasburg Dam. The discharge of the Rio Grande in the Mesilla Valley is regulated by releases from these two reservoirs and diverted into an extensive network of canals. An extensive network of drains carries return flows back to the river. Percha Dam, Leasburg Dam, and Mesilla Dam are diversion dams along the Rio Grande that divert water into irrigation canals. Percha Dam diverts water for the Rincon Valley, Leasburg Dam diverts water for the northern portion of the Mesilla Valley, and Mesilla Dam diverts water for the southern portion.

Streamflow in the river and the amount of water diverted for irrigation may vary greatly from year to year. Surface water is supplemented by groundwater primarily in years when surface supplies are insufficient for crop requirements. Groundwater is used for all domestic water needs both public and private.

Several arroyos flow into the Rio Grande mainly from the mountains on the east side of the basin. Flow in some of the large arroyos is blocked by retention dams near Las Cruces and El Paso. Flow in other arroyos reaches the valley, but probably does not contribute much flow to the discharge of the Rio Grande.

The two principal mechanisms for recharge in the Mesilla basin is seepage from the Rio Grande and from deep percolation of applied irrigation water. The convergence of the surface flow from time to time into arroyos where it can rapidly infiltrate deep into the alluvial sediments may provide a secondary mechanism for natural recharge of groundwater. This type of recharge is referred to as mountain front recharge or slope front recharge (Frenzel and Kaehler, 1990). Mountain and slope front recharge comprise only a very small portion of total recharge to the Mesilla basin aquifers.

History of Groundwater Development

In the Mesilla Valley, agriculture is a major activity. Agriculture in the valley is irrigated by surface water from the Rio Grande Project, which consists of Elephant Butte and Caballo reservoirs. Discharge from the reservoirs has been highly variable over time, due to variances in the hydrologic cycle and differing operational parameters. The flow into Elephant Butte Reservoir has averaged about 904,000 acre-feet per year (1895-1985) and past the Elephant Butte gaging station about 872,000 acre-feet per year (1915-1992).

Historically, irrigators have used irrigation practices that effectively use the groundwater system as a reservoir in a combined stream-aquifer system. During years of plentiful surface water, irrigators divert most of the irrigation water from the Rio Grande. According to Blaney and Hanson (1965) about two thirds of the applied irrigation water may replenish the groundwater system. However more recent studies in the Mesilla Valley (Sammis 1996, personal communication) has shown that only about one third of the applied irrigation water seeps into the groundwater system. Some groundwater seeps into drains that discharge to the Rio Grande. During years of inadequate surface water supply, the shortfall is made up from groundwater causing lower than usual groundwater levels and diminished drain discharge. Groundwater levels generally recover after a normal irrigation season. Studies conducted in the wells installed by the Bureau of Reclamation have shown that the water table in the Mesilla Valley fluctuates about four feet between the irrigation and nonirrigation season.

Groundwater Investigations

Groundwater investigations have been conducted in the Mesilla basin since the early 1900. Slichter (1905) was one of the first to report on the groundwater conditions of the Mesilla Valley. His report included information about well occurrence, pumping rates, and depth to water table. Lee (1907) provided a more detailed record of the geology, depth to water, hydraulic gradients and water quality for the shallow aquifer (Rio Grande Alluvium) of the Mesilla basin during predevelopment years.

The earliest comprehensive reports of hydrology of the area are in U.S. Geological Survey Water Supply Papers by Sayre and Livingston (1945), Conover (1954), Knowles and Kennedy (1958) and Leggat, Lowry and Hood (1962). King and others (1971) discussed both the geology and groundwater resources of the Las Cruces area. This report was followed by a more comprehensive work on the hydrogeology of the region by Wilson and others (1981). Wilson and White (1984) presented aquifer test data for the central Mesilla Valley, and Myers and Orr (1985) presented aquifer test data for the northern West Mesa area. A report by Hernandez and others (1987) included estimates of municipal water use for 1984. Nickerson (1989) reported aquifer test data based on the stage changes in the Rio Grande. Hawley and Lozinsky (1992) reviewed electric logs, identifying upper, middle, and lower hydrostratigraphic units of the Santa Fe Group. Groundwater flow model studies include Gates and others (1984), Peterson and others (1984), Frenzel and Kaehler (1990), Frenzel (1992) and Hamilton and Maddock (1993).

Geologic/Geohydrologic Setting

Regional structure

The Mesilla basin aquifers (Figures 1.2 and 2.1) are defined geologically and hydrologically by structural boundaries. They are bounded by uplifted blocks of bedrock or by relatively impermeable volcanic rocks and are filled with alluvial sediment from surrounding mountains and with fluvial sediment carried in by the ancestral Rio Grande. The Mesilla basin is at the southern end of a north-trending series of structural basins and flanking mountain uplifts that comprise the Rio Grande rift (Chapin and Seager, 1975; Seager and Morgan, 1979; Chapin, 1988). The rift extends through New Mexico from the San Luis Basin of south-central Colorado to the Hueco Bolson and Bolson de los Muertos area of western Texas and northern Chihuahua, Mexico (Hawley, 1978).

The area's geology (Figure 2.2) includes numerous mountain ranges and outcrops forming impermeable and semi-impermeable boundaries for the intermontane bolsons and the valley of the Rio Grande. For the most part, the mountains in the region consist of fault-block uplifts with a general north-south trend (Kottlowski, 1958).

The Robledo Mountains consist of a tilted fault-block uplift that has the form of a wedge-shaped horst. They are bound on the east and west by faults and tilt toward the south. The peaks and high ridges are mostly underlain by thick-bedded carbonate rocks of Paleozoic age. The western portion of the Mesilla basin commonly is called the West Mesa. The West Mesa is approximately 300 feet above the present valley floor. The West Potrillo Mountains reflect the primary form of the basaltic volcanic cones and flows that underlie the West Mesa. The Aden Hills, the Sleeping Lady Hills, and the Rough and Ready Hills are comprised of a belt of small peaks, ridges, buttes, and elongated mesas underlain by Tertiary volcanic rocks. The Sierra de Cristo Rey and the Sierra de Juarez are in Mexico. To the east, Goat Mountain is similar in composition to that of San Diego Mountain. Small fault-block uplifts form Tortugas Mountain and Bishop Cap Mountain. The San Andres, San Augustin, Organ and the Franklin Mountains are similar in composition to the Caballo Mountains (King and others, 1971).

Productive aquifers in the Mesilla basin occur in both late Pleistocene to Holocene-Rio Grande alluvium deposits and the upper Tertiary and Quaternary unconsolidated sedimentary deposits of the Santa Fe Group. Generally, the groundwater system of the Mesilla basin is divided into three zones based on lithology, borehole geophysical logs, chemical quality of water and the differences in water levels under stress. The shallow zone is referred to as floodplain alluvium deposits and basin fill deposits within the Mesilla Valley and consists of a mixture of gravel and coarse sand. The formation below the floodplain alluvium, Santa Fe Group deposits, refers to alternate layers of fine to coarse-grained sand, silty clay, and some gravel. Lenticular deposits of silty clay occur throughout the sand deposits which have predominantly medium to fine grain sizes. The deep zone of the Santa Fe Group aquifer consists of a more uniform fine to medium grain size with some silt and clay (Nickerson, 1989). Frenzel (1992) divided the system into the Rio Grande Alluvium deposits and three hydrostratigraphic units within the Santa Fe group.

The surface drainage of the Mesilla basin covers approximately 11,000 square miles. The Rio Grande enters the basin through Selden Canyon, between the Robledo Mountains and the Doña Ana Mountains, and exits through the El Paso narrows, between the Franklin Mountains and the Sierra de Cristo Rey. The Mesilla Valley, created by the latest incision of the Rio Grande, extends from Leasburg to northwest El Paso along the eastern portion of the Mesilla basin. The altitude of the valley ranges from 3,980 feet at Leasburg Dam to 3,729 feet at the El Paso narrows. The Mesilla Valley is about 50 miles long and is about 5 miles across at its widest section. The Mesilla Valley covers an area of approximately 110,000 acres (Frenzel and Kaehler, 1990).

Depositional history

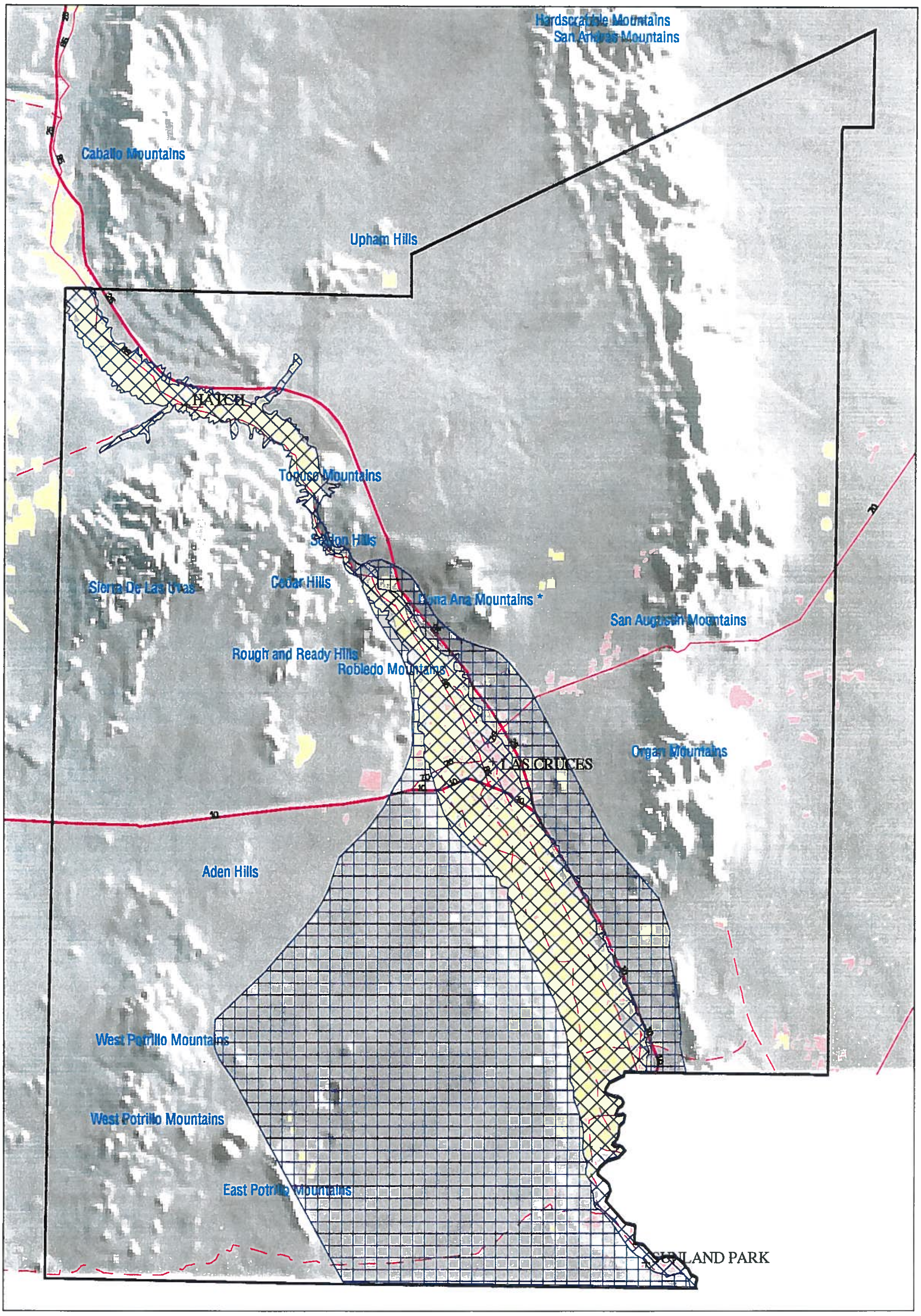
The bolsons within the study area contain groundwater systems primarily consisting of basin-fill aquifers composed of unconsolidated alluvial deposits. The aquifer system may be divided into two main geologic units: the Rio Grande floodplain alluvium and the Santa Fe Group (King and others, 1971). It was deposited by the latest incision of the Rio Grande from the late Pleistocene to the Holocene age. Beneath the Rio Grande floodplain alluvium is the Santa Fe Group. The Santa Fe Group is an intermontane basin-fill unit composed of alluvial deposits of Miocene to middle Pleistocene age (Wilson and others, 1981). The Santa Fe Group can further be broken down into three facies:

- alluvial-fan facies, composed of various size sediments ranging from gravel to clay, which is formed by the erosion of the nearby hills and mountains.

- clay facies, possibly produced by the continued erosion of alluvial-fan facies, deposited in ancient lake and playa deposits, and by deposition of overbank deposits due to seasonal flooding; and

- fluvial facies, consisting of well-sorted sand and gravel deposited axially by the Rio Grande and its major arroyos (King and others, 1971). Because the layers were directly deposited by the Rio Grande, the horizontal permeability greatly exceeds the vertical permeability, usually by several orders of magnitude (Wilson and others, 1981).

Within the Mesilla basin the Santa Fe Group is laterally divided by Pleistocene age normal faults called the Jornada fault zone. These faults split the Mesilla Bolson from the Jornada del Muerto Bolson along a transect north to south from the Doña Ana Mountains, through Tortugas Mountain, to Bishop Cap Mountain. A hydrologic connection between the aquifers exists along this fault zone. Frenzel (1992) estimated that the inflow to the Mesilla was equal to the discharge from the Jornada. Shoemaker (1996) estimated the discharge from the Jornada to the Mesilla along the common boundary to be equal to about 2,860 acre-feet per year.



LAND USE SOURCE: U.S. Geological Survey, 1990. EPA Land Use and Land Cover Digital, Data from 1:250,000--and 1:100,000-Scale Maps —Data Users Guide 4, 1:250,000 QUAD LAND USE, 1982. Contact: Ed Partington at EPA, Phone (703) 235-5595.

SHADED RELIEF: Shaded relief based on USGS DEM files for the state of New Mexico. Processed by Earth Data Analysis Center, Albuquerque, NM, USA.

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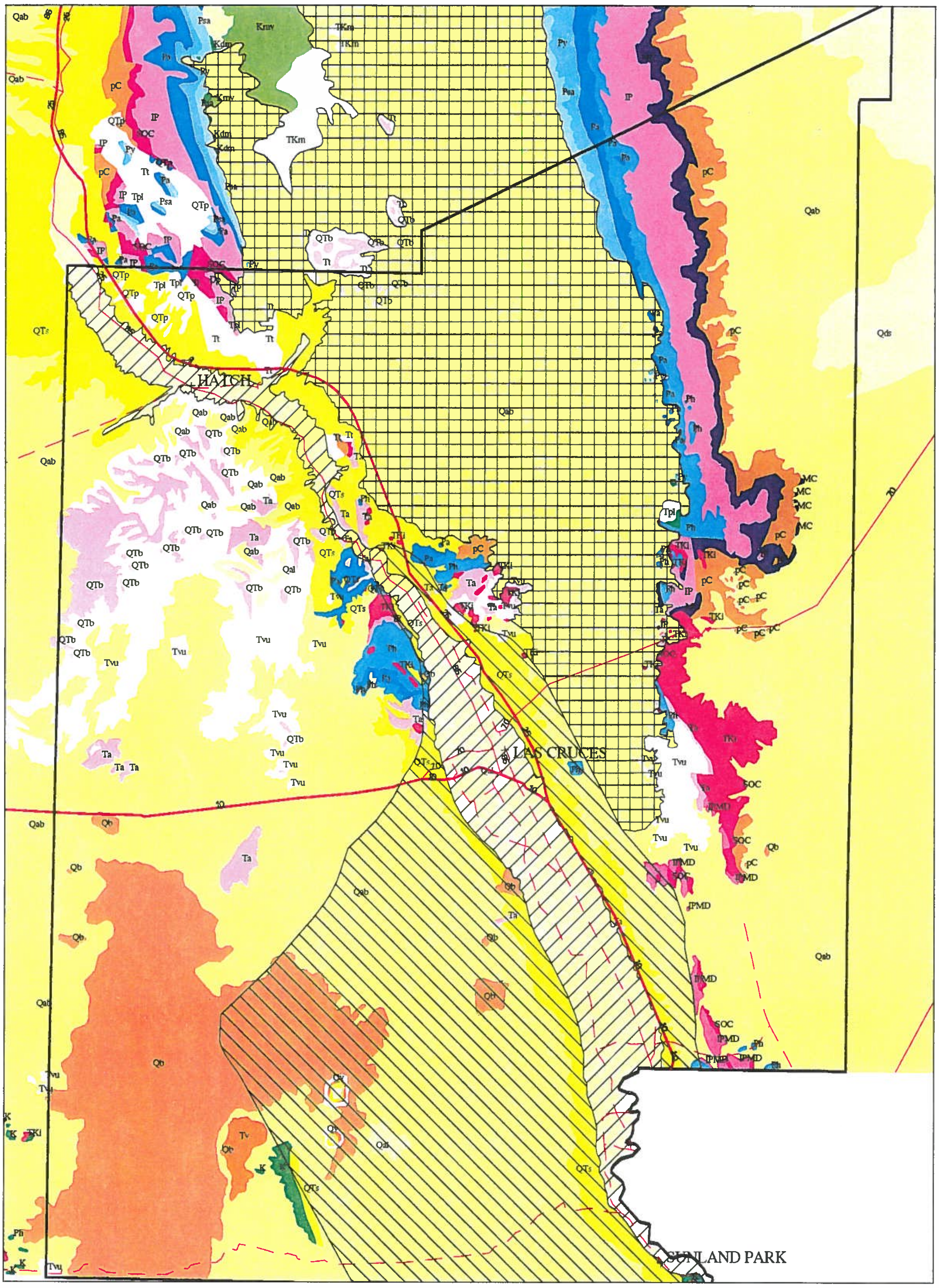
Figure 2.1. Shaded Relief Map with Urban and Agricultural Land Use



Explanation

- 🟥 Interstate
- ⁄ US Highway
- ⁄ State Highway

- ▧ Mesilla Bolson
- ▨ Rio Grande Alluvium
- ▦ Jornada del Muerto

SOURCE: Dane and Bachman 1965, Geology of New Mexico, 1:500,000 map. USGS in cooperation with New Mexico Tech, New Mexico Bureau of Mines & Mineral Resources, and UNM, Geology Dept., (digital file scanned and georeference corrected by USGS/WRD).

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Figure 2.2. Surface Geology of Dona Ana County, New Mexico

RIO GRANDE FLOODPLAIN ALLUVIUM

The Rio Grande Floodplain Alluvium is not a confined aquifer and consists of alternating and interfingering layers of clay and fluvial facies. The alluvium generally runs the width of the valley and is approximately 80 feet deep. Alluvial deposits extend laterally for hundreds of feet beyond the valley slopes (Wilson and others, 1981). The floodplain alluvium has a basal gravel layer about 30 to 40 feet thick. The water table in the valley is approximately 10 to 25 feet below the land surface. Groundwater within the alluvium is generally unconfined and typically moves southeastward down the valley at an average gradient of about 4 to 6 feet per mile; however, the direction is somewhat influenced by nearby hydraulic structures such as the river, drains, canals, well pumpage and heavily irrigated fields (Wilson and White, 1984).

The majority of discharge from the floodplain alluvium occurs through evapotranspiration of irrigated crops, flow to drain system, irrigation pumpage, municipal pumping, and industrial pumping. A small amount of river underflow exits at El Paso narrows (Slichter 1905). According to Wilson and others (1981), transmissivity values range from 10,000 to 30,000 ft^2/day. This transmissivity values translates into hydraulic conductivity of 100 to 350 ft/day. Frenzel (1992) estimated a specific yield value of 0.2.

Recharge

The majority of recharge to the floodplain alluvium is through applied irrigation water and seepage from the Rio Grande and its tributaries. A small amount of underflow probably recharges the alluvium at Selden Canyon (Frenzel, 1992). This possible underflow recharge at Selden Canyon was also confirmed by Avalos (1994). An example of this recharge occurred on January 15, 1986, when an abrupt rise in Rio Grande stage due to a scheduled upstream release caused a rapid rise of groundwater levels. This rapid response of groundwater levels to a rise of flow in the Rio Grande indicates a strong hydraulic connection between the river and the floodplain alluvium. Records of mean daily water levels in monitoring wells maintained by the USGS and mean daily river stage clearly indicate that the water levels in the wells in the floodplain alluvium follow the trends of the river stage throughout the year. Recharge from precipitation is considered minor. The net recharge to the aquifer is directly related to Rio Grande streamflow and the volume of river water used for irrigation (Nickerson and Myers, 1993). The Rio Grande acts both as a gaining as well as a losing stream along its 60 mile length from Leasburg Dam to El Paso narrows (Hamilton and Maddock 1993).

Discharge

Most groundwater discharge from the Alluvium takes place in the vicinity of the valley-margin and floodplain surfaces (Nickerson and Myers, 1993). This discharge occurs in several different ways:

- flow to agricultural drains
- seepage to the Rio Grande in the gaining reaches of the stream
- well discharge
- evapotranspiration
- discharge from interbasin groundwater outflow is considered minor (Wilson and others, 1981)

When the water table in the floodplain alluvium aquifer intersects a drain channel, discharge to the channel occurs. Some drains flow all year, while others flow periodically, varying with water levels in the shallow aquifer. Much of the irrigation water that infiltrates to the water table is thus returned by drains to the river (Nickerson and Myers, 1993).

Discharge to the Rio Grande in the gaining reaches of the river occurs when the potentiometric surface of the aquifer rises above the river stage. Seepage investigations show that the Rio Grande is usually a losing stream through most of the Mesilla Valley. Gains, however have been reported between Leasburg Dam and Las Cruces (Wilson and others, 1981) and immediately upstream from the El Paso narrows in the southern end of the Mesilla Valley.

Hydrologic Characteristics

The specific capacities ranges from 10 to 217 gpm/foot drawdown with an average of 69 gpm/foot drawdown. Based on these specific capacities of shallow irrigation wells that perforated the floodplain alluvium south of Las Cruces, the transmissivity was estimated to range from 10,000 ft^2/day to 20,000 ft^2/day (Wilson and White, 1984).

Water Quality

An attempt was made to evaluate if water quality degradation had occurred over time by plotting conductivity and nitrates vs time over an extended period. This was less informative than hoped because there were no shallow wells with a complete long term record.

MESILLA BOLSON

The major source of the fresh groundwater within the Mesilla Bolson is from the Quaternary-to-Tertiary age Santa Fe Group. The extent of the aquifer system within the Santa Fe Group is controlled by the surrounding faults which create an effective barrier to groundwater flow, although a small amount of flow may enter or leave the bolson at low barrier points.

Saturated Thickness

The Santa Fe Group has thick sequences of clay and silt facies that interfinger with fluvial facies, which create confined/leaky aquifer conditions in the basin fill. The largest amounts of freshwater can be found in the fluvial facies. This facies varies in depth, due to the volcanic activity within the region, from 280 feet in the northern part of the bolson to over 2,000 feet near the center of the bolson. In some areas of the northern West Mesa, the fluvial facies extends to depths close to 2,500 feet below the surface. In the southern section of the bolson, well fields near Canutillo, Texas withdraw a substantial amount of water from depths up to 1,100 feet below the surface. The southeastern sections of the bolson contains a thick clay facies. At the El Paso narrows, a bedrock high prevents much of the groundwater from leaving the valley.

Hydrologic Characteristics

The Santa Fe Group hydrological characteristics vary from place to place due to heterogeneity of its lacustrine, playan, fluvial and alluvial deposits. Hawley and Lozinsky (1992) defined the Santa Fe Group as consisting of three hydrostratigraphic units which are referred to as upper unit, middle unit and deep unit. The upper unit is generally only saturated in the northern third of the bolson and consists of gravels with lenticular deposits of clay. This unit may be the most permeable based on larger grain sizes and less cementation. The middle hydrostratigraphic unit is less permeable than the upper unit due to a greater degree of cementation. This unit also consists of gravel and lenticular deposits of clay. The lower unit consists of a uniform fine sand and averages approximately 600 feet in thickness. In general, the basin fill deposits of the Santa Fe Group are deep under the Mesilla Valley and generally thin toward the basin edges. The maximum thickness of Santa Fe Group deposits is estimated as approximately 2,500 feet. The lower hydrostratigraphic group rests on a bedrock of limestone conglomerate which is generally considered impermeable. Frenzel (1992) estimated hydraulic conductivity's ranging from 2 - 68 ft/day, 1 - 100 ft/day, and 1 - 34 ft/day for upper, middle and lower hydrostratigraphic units respectively. The median hydraulic conductivity estimates fall at 25 ft/day for the upper unit, between 13 - 14 ft/day for middle unit and between 11 - 14 ft/day for the lower unit.

Other authors (Nickerson, 1989; Myers and Orr, 1985; Alvarez and Buckner, 1980) have provided estimates of transmissivity based on pump tests. Nickerson (1989) reports transmissivity of 2,600 ft^2/day and less than or equal to 4,700 ft^2/day for the upper intermediate and deep zones and storage coefficient of 0.00043 for the Santa Fe Group aquifer at Canutillo. Myers and Orr (1985) studied aquifer properties in the West Mesa area and calculated transmissivity of 5,900 ft^2/day for a well screened at selected intervals between 710 to 1,210 feet below surface. The authors concluded that this was probably conservative and that transmissivity may be as great as 6,800 ft^2/day. Spiegel (1972) estimated transmissivity of 10,000 ft^2/day and a storage coefficient of 0.00002 for a well in the northern section of West Mesa. Gates and others (1984) reported a storage coefficient of 0.0007 for the medium-depth and deep aquifers under the floodplain within the Mesilla Valley. Avalos (1994) calculated transmissivity values ranging from 800 ft^2/day to 6000 ft^2/day for the City of Las Cruces Well Field. Based on aquifer tests, the transmissivity ranged from 10,900 ft^2/day to 40,000 ft^2/day throughout the bolson. The average horizontal hydraulic conductivity was 67 ft/day. These tests also provided evidence that the horizontal hydraulic conductivity apparently decreases with depth (Wilson and White, 1984). Vertical hydraulic conductivity values were found to range from 0.21 ft/day to 3.0 ft/day for the entire thickness of the confining layer.

Recharge

The majority of recharge to the Santa Fe Group aquifer occurs through mountain front recharge along the Franklin, Organ, Robledo, West Potrillo and East Potrillo mountains, and the Aden-Sleeping Lady, Rough and Ready Hills complex and through vertical flow of groundwater from the floodplain alluvium in the Mesilla Valley region. Recharge into the Santa Fe Group from the groundwater in the floodplain alluvium moves down through layers of sand and around clay layers. Cones of depression also influence the movement of groundwater into the Santa Fe Group.

Discharge

The majority of the discharge from the Santa Fe Group aquifer system occurs as municipal and industrial pumping in the Mesilla Valley. It is clear from plotting of USGS water-level data that the municipal cones of depression from Las Cruces and Canutillo have a significant regional impact on the direction of groundwater flow (Figure 2.3). The potential impact of this change in the local groundwater flow direction was further investigated in the particle tracking work by Hanson and Samani (1995).

Water Quality

The general water quality in the Mesilla basin aquifers is shown by the use of stiff diagrams in Plate 1. The reader is cautioned that the stiff diagrams do not provide information on the depth of the water sample which can strongly influence the quality. There is an overall general trend of decreasing dissolved solids concentration with depth. This may be attributed, in part to the effects of surface irrigation practices and evapotranspiration (Frenzel and others, 1990). As part of the applied water evaporates or is transpired, the dissolved solids in the water are concentrated. This water is recharged to the shallow groundwater system. Frenzel and others (1990) described the factors in the valley which will have a major impact on water quality in the Mesilla Bolson. From their analysis the current irrigation practices allow the soils in the valley to be kept flushed of salts. Most of the flushing water tends to be captured by the drain system and returned to the river. Some may move into the shallow groundwater.

This shallow groundwater can be mixed into the deeper high quality groundwater through pumping activity. The cone of depression formed by the pump may act as a mixing zone. Wilson and White (1984) reported on pumping tests for five EBID wells during the 1976 - 78 irrigation seasons. Four of the five wells showed no change in water quality from pumping. The fifth well showed a reduction in water quality. It appeared that the wells that did not show a reduction in water quality were constructed in a manner that prevented poorer quality shallow water from moving down into the screened zone. It was noted that irrigation wells constructed with cement casing or blank casings set in a thick clay layer at approximately 200 feet or more below the land surface produce the water with the smallest specific conductance. Thus it appears that good construction practices can minimize the impact of localized vertical mixing.

Volume with TDS less than 10,000 mg/L

Wilson and others (1981) estimated the thickness of the saturated sediments in the Mesilla Bolson containing freshwater (<300 mg/L TDS) from Less than 400 feet near the edges to more than 2,400 feet near the center of the Mesilla Valley. He estimated the volume of the freshwater in storage beneath the Mesilla Valley, with the thickest zone generally following the present course of the Rio Grande, to be about 66 million acre-feet and an additional 34 million acre-feet beneath the West Mesa (Wilson, et al., 1981).

Avalos (1994) estimated the freshwater zone of the mesilla Bolson to be limited to the top two layers of the aquifer, with an average thickness of 700 feet and a surface extent of about 612 thousand acres. With a specific yield of 0.2 (Frenzel and Kaehler, 1990) then the volume of freshwater would be about 85.7 million acre-feet.

JORNADA DEL MUERTO BOLSON

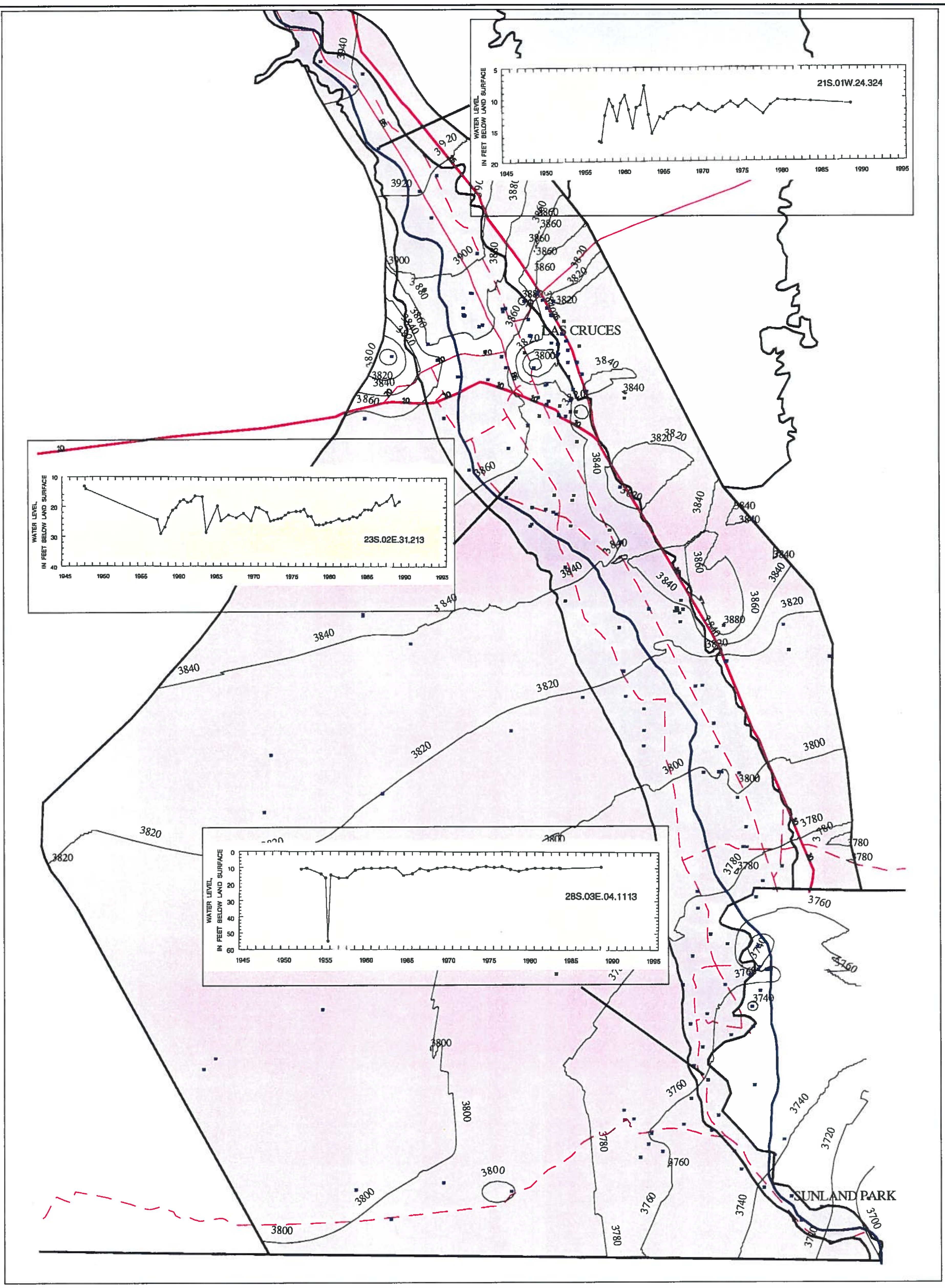
Location and Extent

The Jornada del Muerto Bolson is east of the Rio Grande Valley. It is bordered by the Caballo Mountains and Point of Rocks to the west, the Doña Ana Mountains, San Diego Mountain, and Tortugas Mountain to the southwest, and the Organ Mountains and the San Andres Mountains to the east. The Point of Rocks appears to be the remnant of a former cover of andesites, basalts, rhyolite tuffs, and associated sedimentary rocks, that have been disrupted by a combination of erosion, faulting, and warping. The Doña Ana Mountains are domal uplifts composed mainly of Tertiary igneous rocks. San Diego Mountain appears to be a peak formed by the erosional remnant of Tertiary igneous intrusive rock. Tortugas Mountain is a small fault-block uplift. The Organ Mountains and the San Andres Mountains are similar in composition to the Caballo Mountains (King and others, 1971).

The Jornada del Muerto Bolson covers approximately 3,344 square miles and is approximately 12 miles across at its widest section. It does not have a noticeable boundary with the Mesilla Bolson. The two bolsons are separated by a subsurface Tertiary volcanic rock high bounded by normal faults that extend from the Doña Ana Mountains to Tortugas Mountain, to Fillmore Pass. There is no evidence that the Rio Grande ever flowed through the Jornada del Muerto Bolson (King and others, 1971). The latest incision of the Rio Grande was restricted from entering the Jornada del Muerto Bolson by the Caballo Mountains (King and others, 1971).

Hydrologic Characteristics

The Santa Fe Group in the Jornada del Muerto Bolson is composed of a fluvial facies, a clay facies, and an alluvial-fan facies. Throughout the bolson, the fluvial facies is usually above the water table. The portion of the bolson that is south of the Point of Rocks and north of the Doña Ana Mountains has a fluvial facies layer that is more than 325 feet deep. It is possible that the lowest portions of this facies dips below the water table. The zone of saturation is most likely in older alluvial-fan deposits or in the fine-grained units of the clay facies. The clay facies is the predominant facies in the zone of saturation in the northern and extreme southern sections of the Jornada del Muerto Bolson. Water production is mainly in the southern region of the Jornada del Muerto on the lower slopes of the large alluvial-fan facies north of Highway 70 and south of the Point of Rocks. The depth to the water table is between 300 to 575 feet and the thickness of the satu-



NEW MEXICO AQUIFER SOURCE: Kernodle, J. M., 1992, Summary of U.S. Geological Survey Ground Water Flow Models of Basin-fill Aquifers in the Southwestern Alluvial Basins Region, Colorado, New Mexico, and Texas: U.S. Geological Survey, Open-File Report 90-361, Albuquerque, New Mexico.

USGS MONITORING WELLS SOURCE: Wilkins, D.W., and Garcia, B.M., 1995. Ground-water Hydrographs and 5-year ground-water-level changes, 1984-93, for selected areas in and adjacent to New Mexico: U.S. Geological Survey Open-file Report 95-434, Albuquerque, New Mexico.

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Explanation

- ▪ USGS Monitoring Wells
- ∧ Water Level Contour Lines 20 foot interval
- ∧ Interstate
- ∧ US Highway
- ∧ State Highway
- ∧ Rio Grande
- ▭ Mesilla Bolson
- ▭ Rio Grande Alluvium
- ▭ Jornada del Muerto

SCALE 1:250000

1 0 5 10

KILOMETERS

Figure 2.3. Water Level Contours and Selected Hydrographs for the Mesilla Bolson and Rio Grande Alluvium Aquifers

rated sediment is between 400 to 500 feet. Four wells drilled into the large alluvial-fan of the southern San Andres Mountains have penetrated more than 1,000 feet of alluvial sediment and pump a substantial amount of water (King and others, 1971). The City of Las Cruces currently is in the process of establishing a well field in the southern portion of the Jornada del Muerto Bolson. Shoemaker and Finch (1996) in a report prepared for the City of Las Cruces estimated that the ultimate rate of annual withdrawal from the aquifer could be about 9,000 acre-feet per year.

Groundwater Movement

Groundwater movement in this bolson varies greatly. The groundwater in the northern part of the bolson moves south down the valley and west toward the Rio Grande into the Rincon Valley at an average gradient of 150 feet per mile. Groundwater from the southern part of the bolson moves north and west into the Rincon Valley at an average gradient of 10 feet per mile. There is some evidence that groundwater in the southern section may move west across the subsurface igneous boundary into the Mesilla Bolson through subsurface channels that have been eroded through the boundary. It has been speculated that large amounts of fresh water could be pumped from one of these channels (Wilson and others, 1981). Shoemaker and Finch (1996) estimated that subsurface groundwater flow across the boundary from the Jornada del Muerto into the Mesilla Bolson amounted to about 2,860 acre-feet per year. Frenzel's (1992) model estimated about 3,790 acre-feet of flow per year from the Jornada into the Mesilla across their common boundary. The specific capacities for wells in the southern section of the Jornada del Muerto Bolson is about 5 gpm/foot drawdown. Estimated transmissivity values in this area range from 5,000 ft^2/day to 15,000 ft^2/day (Wilson and others, 1981).

Recharge

Recharge into the Jornada del Muerto Bolson occurs primarily from precipitation and infiltration of mountain front runoff through major arroyos (Frenzel and Kaehler, 1990).

Water Quality

Groundwater in the southern section of the Jornada del Muerto Bolson is classified as fresh. The hardness of the water ranges from 24 to 320 mg/l. Water in the northern section of the bolson is classified as slightly saline. In the Rincon Valley, where most of the groundwater is discharged, dissolved-solids concentrations taken from depths of 130 ft to 150 ft, and 250 ft to 280 ft were 1,800 and 2,820 mg/L respectively. Both Shoemaker and Finch (1996) and Icerman and Lohse (1983) reported that some water enters the aquifer in the form of geothermal water moving upward, presumably along a fault zone or zones, in the area east of Las Cruces. Shoemaker and Finch (1996) estimated the volume to be about 59 acre-feet per year.

WATER USE

Total water use, both surface water and groundwater, is summarized by category in Tables 2.1 through 2.4 for Doña Ana County, New Mexico for the years 1990, 1985, 1980, and 1975, respectively. The groundwater withdrawals numbers are not separated by aquifer source (Alluvium, Mesilla Bolson, or Jornada Bolson) and include withdrawals from each. In 1990 the total water withdrawals for all categories was 513,841 acre-feet of which 145,663 was from groundwater sources (Wilson, 1992). Depletions were 246,279 acre-feet of which 96,895 was from groundwater. Of the 96,895 acre-feet of groundwater depleted in 1990, 73% (70,900 acre-feet) was used by irrigated agriculture, 19% (18,797 acre-feet) was used by public and private domestic water uses (Table 2.1). Water use by irrigated agriculture varies from year to year and depends upon the quantity of surface water available with groundwater use providing a supplemental supply. All public and private domestic needs rely on groundwater. In 1990 there were 32 public water supply systems in the county that pumped 28,956 acre-feet (most of which were measured) with depletions estimated to be 17,410 acre-feet (Table 2.1). These water systems are shown on Figure 2.4.

In 1975 the groundwater depletions in the county were 60,740 acre-feet for all uses, 53,710 acre-feet in 1980, and 50,958 in 1985 (Figure 2.5 and Table 2.5). The irrigated agriculture uses dominate and vary from year to year depending upon the availability of surface water. Excluding irrigated agriculture, the remaining groundwater depletions were 10,980 acre-feet in 1975, 15,380 acre-feet in 1980, 17,509 acre-feet in 1985, and 25,995 acre-feet in 1990 (Sorensen, 1977; Sorensen, 1982; Wilson, 1986; and Wilson, 1992) (Figure 2.6).

SUSCEPTIBILITY TO CONTAMINATION

Land Ownership and Land Use

The federal government is the largest landholder with 1,782,350 acres or 73% of the land in Doña Ana County. Of this total, the Bureau of Land Management (BLM) administers 63% (1,123,833 acres), and the military controls 31% (547,808 acres). The State of New Mexico holds a total of 11% of the land in Doña Ana County, and 16% of the land is privately owned. The largest percentage of private agricultural land in the county lies under the jurisdiction of the Elephant Butte Irrigation District, which administers the delivery of surface water to about 90,730 acres of cropland.

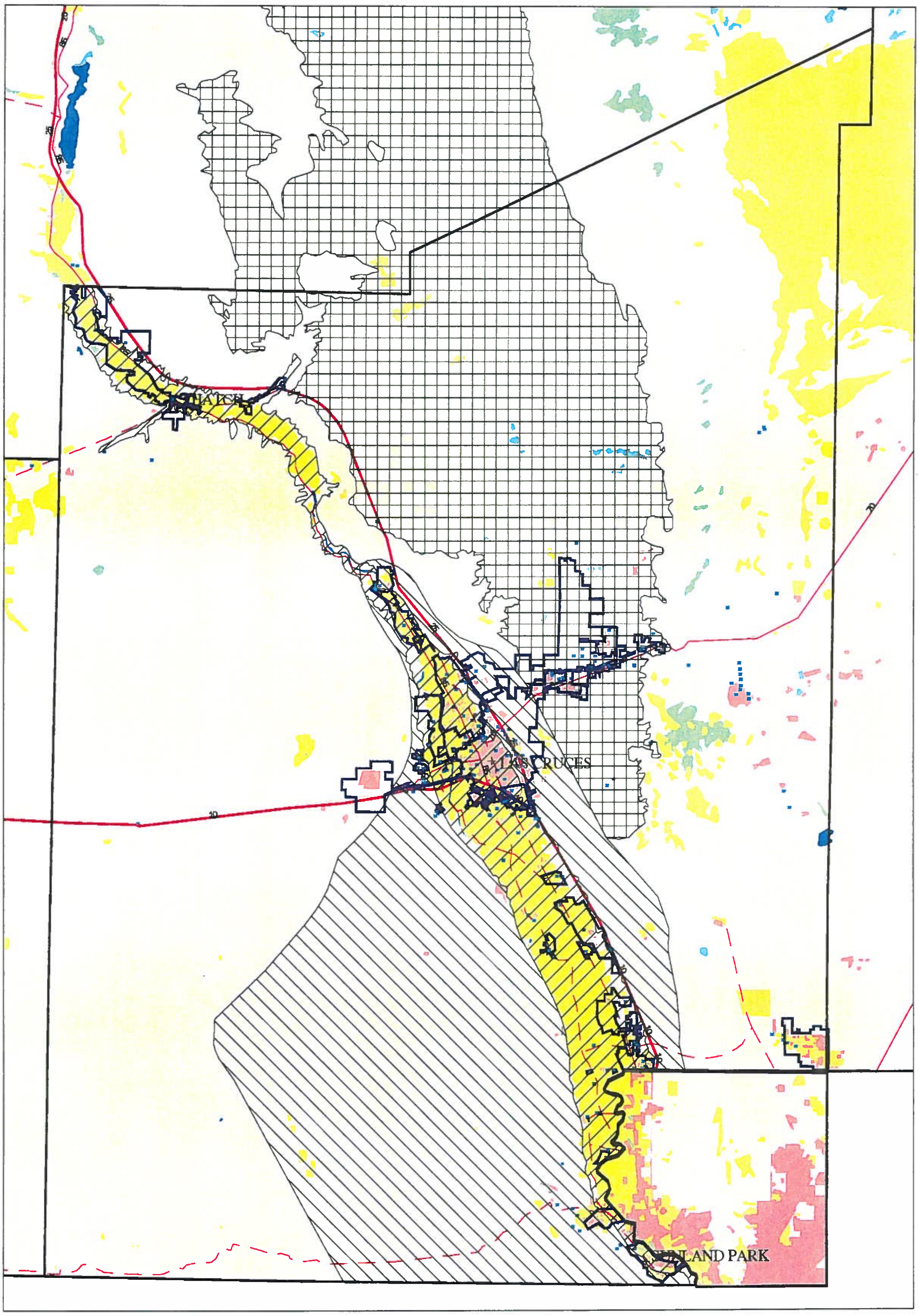
Land use in Doña Ana County is regulated by zoning and subdivision laws adopted by the county under state statutes. Residential developments and business permits are reviewed by state and local agencies. Two zoning authorities administer policy and regulations in the unincorporated portions of Doña Ana County. The Extraterritorial Zoning Commission (ETZ) has jurisdiction within five miles of Las Cruces, and the Doña Ana County Planning and Zoning Commission (PZC) reviews zoning and subdivisions outside of the ETZ and in the unincorporated areas of the county. Sunland Park, Las Cruces, Hatch, and Mesilla are incorporated municipalities, and each has its own zoning and subdivision regulations.

Land-use statistics were reported for two categories of land: vacant lands (undeveloped tracts of federal, state, and private land holdings) and non-vacant lands. This classification was used to show the effects that undeveloped land has on the county's land statistics. The largest category of land use is agricultural (69.9%) followed by residential (16.4%). These percentages are much lower when vacant lands are included. Land use is shown on Figure 2.4. The land use shown on this map is 1982 data. If the agricultural area shown on this map is compared to the public water supply systems also shown on the map, it is apparent that a significant amount of agricultural land has been converted to residential use over the past 14 years. The land use information is of interest if the surface use has a potential impact on groundwater quality. Any activity that produces a soluble contaminant and which provides a transport mechanism (water) is a potential groundwater contamination source. The residential areas with septic tanks, and agricultural areas which perform flood or furrow irrigation are both potential pollution sources.

Special-use permits

Until 1993, zoning in Doña Ana County was carried out through the approval of special-use permits. Each permit application was considered by the PZC, and permits were approved or denied based on review by county staff, state and local agency comments and recommendations, and public comment. Most applications were approved with certain conditions.

In 1993, Doña Ana County adopted a new interim zoning ordinance which prohibits some industrial and commercial land uses until a new comprehensive plan is adopted. The largest non-residential land-use category in Doña Ana County is commercial at 42% with industrial second at 37%. Public (7%) and residential (6%) land uses lie within the miscellaneous category. Interestingly, multi-family residential special-use-permit approvals make up a small percentage of the overall



LAND USE SOURCE: U.S. Geological Survey, 1990, EPA Land Use and Land Cover Digital, Data from 1:250,000–and 1:100,000-Scale Maps —Data Users Guide 4, 1:250,000 QUAD LAND USE, 1982. Contact: Ed Partington at EPA, Phone (703) 235-5595.

WATER SYSTEM SOURCE: Dona Ana County Planing Department, GIS Division. 1996.

DRINKING WATER WELLS SOURCE: New Mexico Environmental Drinking Water Bueru, 1996.

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Figure 2.4. Public Water Wells, Water Distribution Systems, and Land Use in Dona Ana County, New Mexico

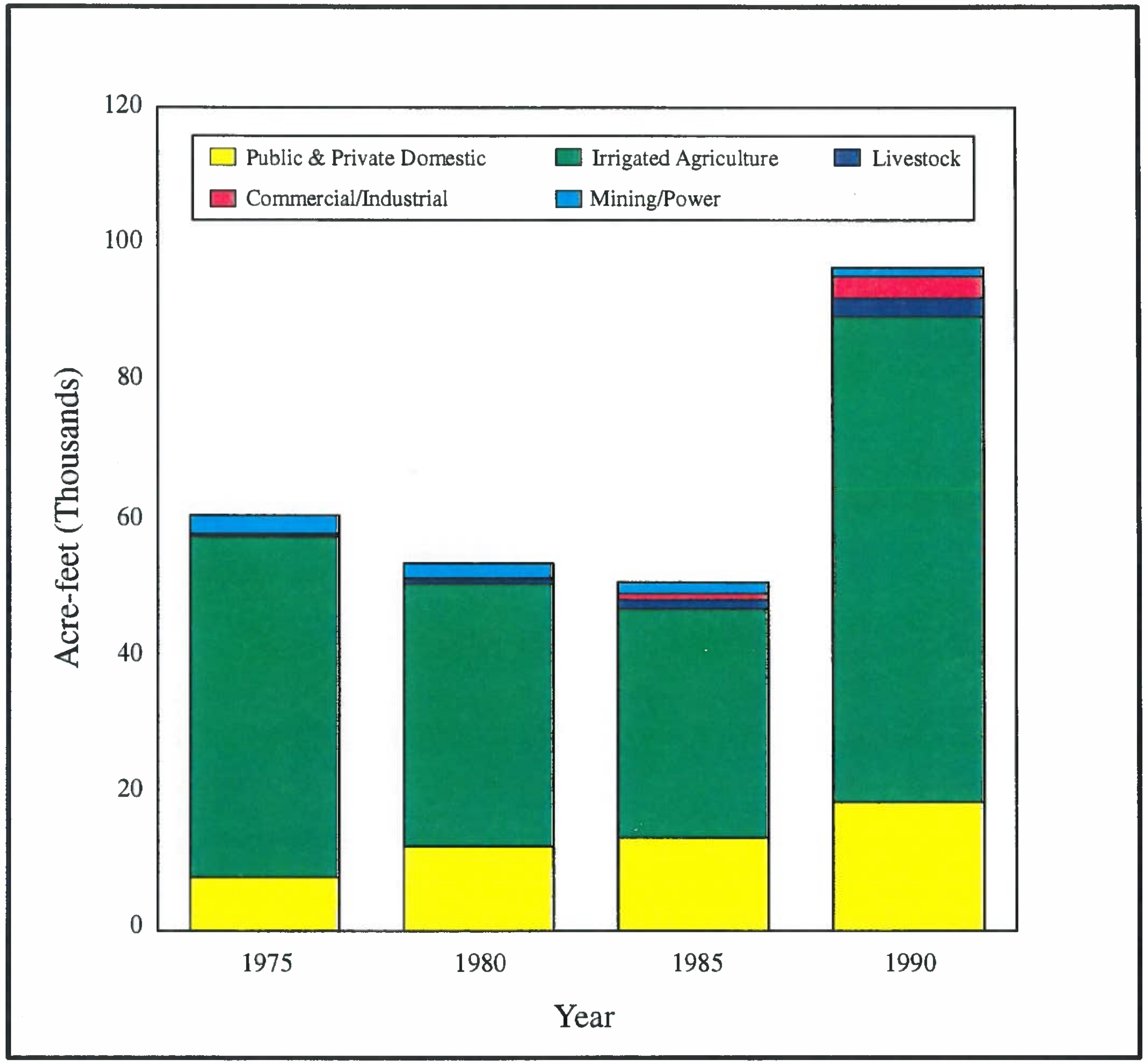


Figure 2.5. Groundwater depletions by category in Doña Ana County, New Mexico for 1980, 1985, and 1990 (source of data, Sorensen, E.F., 1977; Sorensen, E.F., 1982; Wilson, B.C., 1986; Wilson, B.C., 1992).

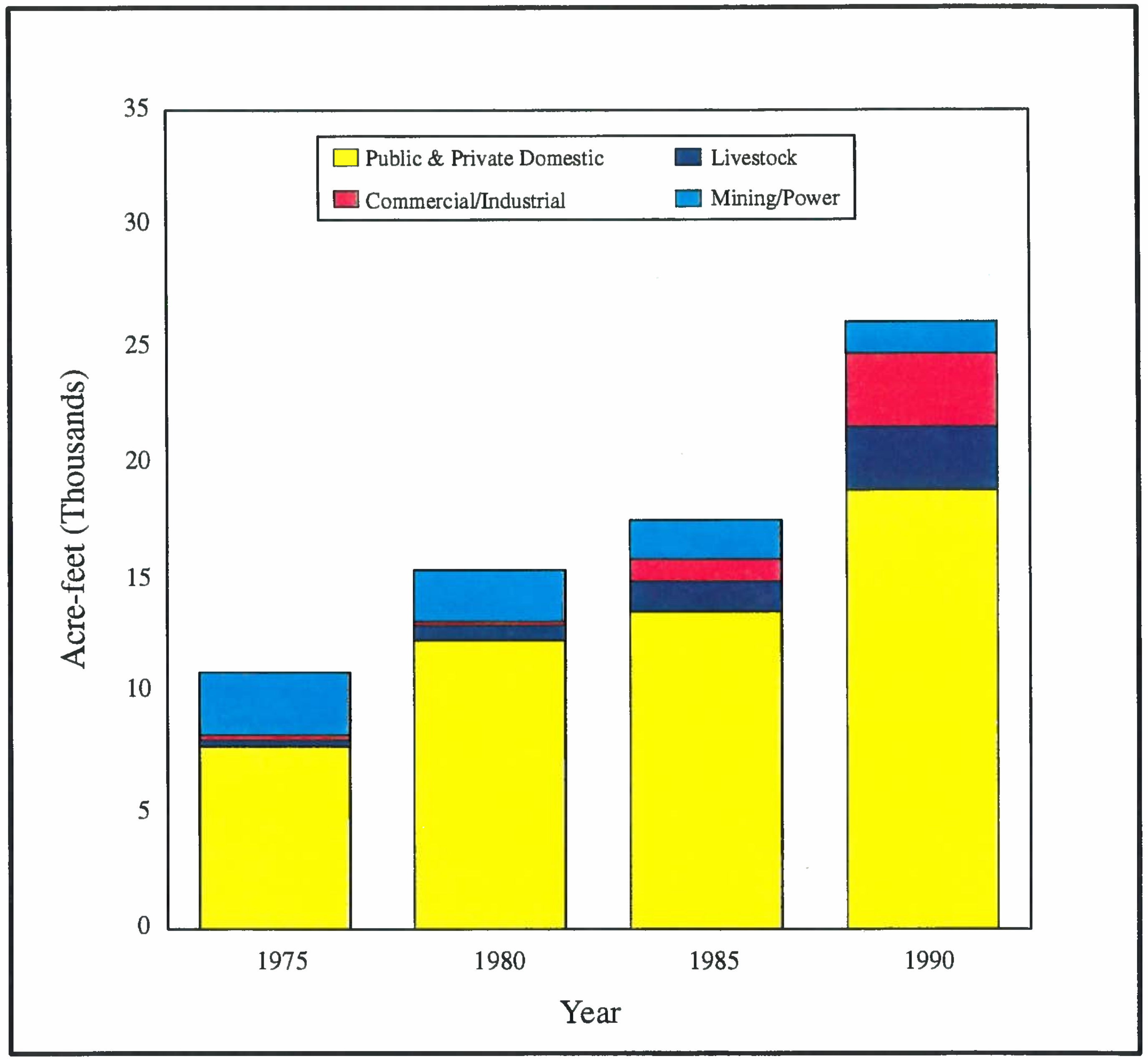


Figure 2.6. Groundwater depletions by category excluding irrigated agriculture in Doña Ana County, New Mexico for 1980, 1985, and 1990 (source of data, Sorensen, E.F., 1977; Sorensen, E.F., 1982; Wilson, B.C., 1986; Wilson, B.C., 1992).

Table 2.1. Water Use by category in Doña Ana County, New Mexico in 1990 in acre-feet.

	WSW	WGW	TW	DSW	DGW	TD	RFSW	RFGS	TRF
Public Water Supply *	0.00	28955.98	28955.98	0.00	17409.69	17409.69	0.00	11546.29	11546.29
Domestic (self-supplied) *	0.00	2311.64	2311.64	0.00	1386.98	1386.98	0.00	924.66	924.66
Irrigated Agriculture	368042.00	104989.00	473031.00	149254.00	70900.00	220154.00	218788.00	34089.00	252877.00
Livestock (self-supplied)	48.04	2977.30	3025.34	48.04	2708.47	2756.51	0.00	268.83	268.83
Commercial (self-supplied)	88.80	4547.25	4636.05	81.70	3077.55	3159.25	7.10	1469.70	1476.80
Industrial (self-supplied)	0.00	129.49	129.49	0.00	69.54	69.54	0.00	59.95	59.95
Mining (self-supplied)	0.00	44.80	44.80	0.00	11.15	11.15	0.00	33.65	33.65
Power (self-supplied)	0.00	1707.09	1707.09	0.00	1331.53	1331.53	0.00	375.56	375.56
Reservoir Evaporation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**368178.84**	**145662.55**	**513841.39**	**149383.74**	**96894.91**	**246278.65**	**218795.10**	**48767.64**	**267562.74**

Column definitions: WSW=Withdrawals Surface Water, WGW=Wighdrawals Ground Water, TW=Total Withdrawals, DSW=Depletions Surface Water, DGW=Depletions Ground Water, TD=Total Depletions, RFSW=Return Flows Surface Water, RFGW=Return Flows Ground Water, TRF=Total Return Flows.

* Detail below list withdrawals and calculated depletions for Public Water Supply and Domestic (self-supplied).

	Measured	WGW	DGW(calculated)
Anthony Water Works	Y	542.60	347.26
Berino Water Users Assn.	Y	196.00	98.00
Butterfield Park MDWCA	Y	84.88	42.44
Chaparral Water System	Y	879.64	439.82
Delara Estates MDWCA	Y	88.33	44.17
Desert Sands MDWCA	Y	77.54	38.77
Doña Ana MDWCA	Y	1,063.06	531.53
Ft. Seldon Subdivision	Y	88.10	44.05
Garfield MDWCA	Y	202.15	101.08
Green Valley MHP	Y	19.00	9.50
Hacienda Acres Water System	Y	286.51	143.26
Hatch Water Supply System	Y	285.44	182.68
Holly Gardems MHP	Y	24.59	12.30
Las Alturas Estates	Y	173.51	86.76
Las Cruces Municipal System	Y	16,904.92	10,142.95
Mesa Development Ctr., Inc.	Y	89.00	44.50
Mesilla Park Manor Water	Y	202.27	101.14
Mesilla Water System	Y	209.46	104.73
Mesquite MDWCA	Y	513.15	256.58
Moongate Water System	Y	563.00	281.50
Mountain View MDWCA	Y	83.69	41.85
Picacho Hills Water System	N	557.98	457.54
Raasaf Hills Water System	Y	16.32	8.16
Rincon Water Consumers Co-op	N	47.77	23.89
Rural self-supplied homes	N	2,311.64	1,386.98
San Andres Estates Water System	Y	127.61	63.81
Santa Teresa Water System	Y	2,356.80	1,932.58
Skoshi Mobile Home Park	Y	18.38	9.19
Sunland Park Water System	Y	870.92	435.46
Talavera Water Co-op1	Y	8.95	4.48
University Estates	Y	424.13	212.07
Vista Real MHP	Y	25.28	12.64
White Sands Missile Range	Y	1,925.00	1,155.00
Total		**31,267.62**	**18,796.62**

Source: Wilson, B.C., (1992)

Table 2.2. Water Use by category in Doña Ana County, New Mexico in 1985 in acre-feet

	WSW	WGW	TW	DSW	DGW	TD
Urban *	0	16021	16021	0	8012	8012
Rural *	0	5399	5399	0	2701	2701
Irrigated Agriculture	376465	58183	434648	139150	33449	172599
Livestock	136	1576	1712	136	1309	1445
Stockpond Evaporation	340	0	340	340	0	340
Commercial	0	1792	1792	0	930	930
Industrial	0	57	57	0	32	32
Minerals	0	181	181	0	60	60
Military	0	2058	2058	0	1235	1235
Power	0	1601	1601	0	1601	1601
Fish and Wildlife	0	0	0	0	0	0
Recreation	160	2485	2645	160	1629	1789
Reservoir Evaporation	0	0	0	0	0	0
Total	**377101**	**89353**	**466454**	**139786**	**50958**	**190744**

Column definitions: WSW=Withdrawals Surface Water, WGW=Wighdrawals Ground Water, TW=Total Withdrawals, DSW=Depletions Surface Water, DGW=Depletions Ground Water, TD=Total Depletions.

Detail below list withdrawals for Urban, Rural and Military.

	Urban/Rural	WGW
Anthony	U	374
Chaparral	U	439
Doña Ana	U	427
Las Cruces	U	14781
White Sands Missile Base	M	2048
Butterfield Park	R	84
Hacienda Acres MHP	R	121
Hatch	R	214
Mesilla	R	188
Mesilla Park	R	158
Pecan Valley Estates	R	36
Rincon	R	43
San Andres Estates	R	113
University Estates	R	138
Other Rural	R	4653
Total		**23817**

Source: Wilson, B.C., (1986).

Table 2.3. Water Use by category in Doña Ana County, New Mexico in 1980 in acre-feet

	WSW	WGW	TW	DSW	DGW	TD
Urban *	0	14179	14179	0	7089	7089
Rural *	0	4878	4878	0	2439	2439
Irrigated Agriculture	395860	58110	453970	166640	38330	204970
Livestock	257	738	995	257	642	899
Stockpond Evaporation	340	0	340	340	0	340
Commercial	0	234	234	0	141	141
Industrial	0	51	51	0	31	31
Minerals	0	181	181	0	59	59
Military	0	2010	2010	0	1209	1209
Power	0	2150	2150	0	2150	2150
Fish and Wildlife	0	0	0	0	0	0
Recreation (land based only)	255	3030	3285	255	1620	1875
Reservoir Evaporation	0	0	0	0	0	0
Total	**396712**	**85561**	**482273**	**167492**	**53710**	**221202**

Column definitions: WSW=Withdrawals Surface Water, WGW=Wighdrawals Ground Water, TW=Total Withdrawals, DSW=Depletions Surface Water, DGW=Depletions Ground Water, TD=Total Depletions.

Detail below list withdrawals for Urban, Rural and Military.

	Urban/Rural	WGW	DGW(calculated)
Anthony	U	220	110
Chaparral	U	—	—
Doña Ana	U	336	168
Las Cruces	U	12070	6035
White Sands Missile Base	M	—	—
Berino	R	20	10
Butterfield Park	R	26	13
Hacienda Acres MHP	R	111	56
Hatch	R	108	54
Mesilla	R	180	90
Mesilla Park	R	117	58
Mesquite	R	68	34
Organ	R	110	55
Pecan Valley Estates	R	31	16
Rincon	R	25	12
San Andres Estates	R	68	34
University Estates	R	170	85
Other Rural	R	3844	1922
New Mexico State Univesity	U	1553	776
Total		**19057**	**9528**

Source: Sorensen, E. F., (1982).

Table 2.4. Water Use by category in Doña Ana County, New Mexico in 1975 in acre-feet

	WSW	WGW	TW	DSW	DGW	TD
Urban	0	9705	9705	0	4852	4852
Rural	0	3508	3508	0	1754	1754
Irrigated Agriculture	412270	72930	485200	153600	49760	203360
Livestock	268	269	537	268	269	537
Stockpond Evaporation	180	0	180	180	0	180
Manufacturing	0	365	365	0	219	219
Minerals	0	181	181	0	59	59
Military	0	2000	2000	0	1200	1200
Power	0	3503	3503	0	2627	2627
Fish and Wildlife	250	0	250	250	0	250
Recreation (land based only)	0	0	0	0	0	0
Reservoir Evaporation	255	0	0	0	0	0
Playa Lake Evaporation	3200	0	3200	3200	0	3200
Total	**416423**	**92461**	**508629**	**157498**	**60740**	**218238**

Column definitions: WSW=Withdrawals Surface Water, WGW=Wighdrawals Ground Water, TW=Total Withdrawals, DSW=Depletions Surface Water, DGW=Depletions Ground Water, TD=Total Depletions.

Source: Sorensen, E. F., (1975).

Table 2.5. Summary of groundwater depletions by category for Doña Ana County, New Mexico, 1975, 1980, 1985, 1990.

	1975	1980	1985	1990
Public & Private Domestic	7806	12357	13577	18796.67
Irrigated Agriculture	49760	38330	33449	70900.00
Livestock	269	642	1309	2708.47
Commercial/Industrial	219	172	962	3147.09
Mining/Power	2686	2209	1661	1342.68
Total	**60740.00**	**53710.00**	**50958.00**	**96894.91**

Sources: Sorensen, E.F., (1977), Sorensen, E.F., (1982), Wilson, B.C., (1986), Wilson, B.C., (1992).

land uses permitted in Doña Ana County. Single family residential and agricultural uses are permitted by right and no special-use-permit is required.

Colonias in Doña Ana County

According to the US Government Accounting Office, a colonia is defined as follows:

- an unincorporated community situated within 100 kilometers of the US/Mexico border
- designated by the county or state in which it is located
- lacking adequate potable water, adequate sewage systems, and safe, sanitary housing
- was in existence before November 1990

By this definition, Doña Ana County has designated thirty-four communities as colonias. Most of these communities are located within the service areas of public water utilities, privately owned water utilities, and water associations. However, due to economic limitations, new residents often have no access to these utilities. The cost of extending water lines is prohibitive, and in many cases, water utilities do not have the capacity to accept new connections. Drilling a domestic water well in the area costs between $5,000 and $8,000. Many residents may dig or drive their own shallow wells and haul in potable water due to the poor water quality in the Rio Grande Floodplain Alluvium aquifer. This wide spread use of shallow wells makes water quality information on the alluvium aquifer of great interest. Unfortunately there appears to be very little water quality data available on the aquifer.

Under the State of New Mexico's 1973 Land Subdivision Act, (Section 47-6-1, et seq., NMSA, 1978) four parcels of land may be divided within three years before subdivision plat approval is required. Therefore, lots may be split without providing access to utilities such as water and sewage disposal. Developers of these marginal subdivisions argue that they provide property ownership opportunities for low-income families. However, the cost of developing utilities becomes a heavy burden on buyers of these undeveloped lots. In some cases, the water table is less than four feet below ground surface, requiring a modified septic tank drainfield. Many homes are built in flood zones without adequate drainage. Families often must haul potable water when local water associations cannot economically extend water lines to these developments.

During the years from 1991 to 1993, the number of building permits issued for mobile homes and site-built homes in the unincorporated areas of the county averaged 1,016, a 4.5% increase in households, per year. This growth was concentrated in the Las Cruces Five Mile-Extraterritorial Zone and the South Valley of the county. This trend was continuing in 1994.

In 1993 the county was ranked as the twelfth poorest in New Mexico in per capita personal income. In many areas, the low income levels have contributed to poor infrastructure development for basic utilities, including drinking water and wastewater treatment. Figure 2.4 shows the location of public water supplies and wells in the Mesilla basin aquifers. Figure 2.7 shows the location of septic tanks in this same region.

From 1980 to 1990, the median income of Doña Ana County residents rose faster than inflation in the county. However, at the same time, the percentage of county residents below the poverty level rose from 22.7% to 26.5% (South Central Council of Governments 1994).

From 1988 to 1993, the labor force in Doña Ana County increased by 7.0% with declining increases each year. In this period, the number of employed persons in the county increased by 5.3%, and the number of unemployed persons increased by 26.9%. Unemployment in each year was lowest in January and highest in June, following the same trend as the size of the labor force.

Agriculture

Most of the region's farming activities are restricted to the valley (Figures 2.1 and 2.4) where the land surface is fairly level and the mean depth to the water table is about 180 cm. The main field crops grown in the area are cotton (22,850 acres), orchards (18,605), alfalfa (15,700), chile (6,000), corn (4,000), and onions (3,900) (Lansford and others, 1996). Crop production is extensively supported by irrigation. Most irrigation is done using flood irrigation systems, with little or no tail-end water.

Historical irrigation practices have used the groundwater system effectively as a reservoir in a combined stream-aquifer system. During years of sufficient surface water, most of the water needed for irrigation is diverted from the Rio Grande. Water levels in shallow observation wells located near the Rio Grande vary with river stage. Water levels in observation wells near the river increase and decline in response to the amount of infiltration of applied irrigation water (Nickerson and Myers, 1993). A portion of the shallow groundwater seeps into irrigation drains that discharge to the Rio Grande. During years of inadequate surface-water supply, groundwater is used as a supplemental water supply. This causes abnormally low groundwater levels resulting in less water being discharged to the drains. Groundwater levels generally return to normal after an irrigation season when surface water is plentiful.

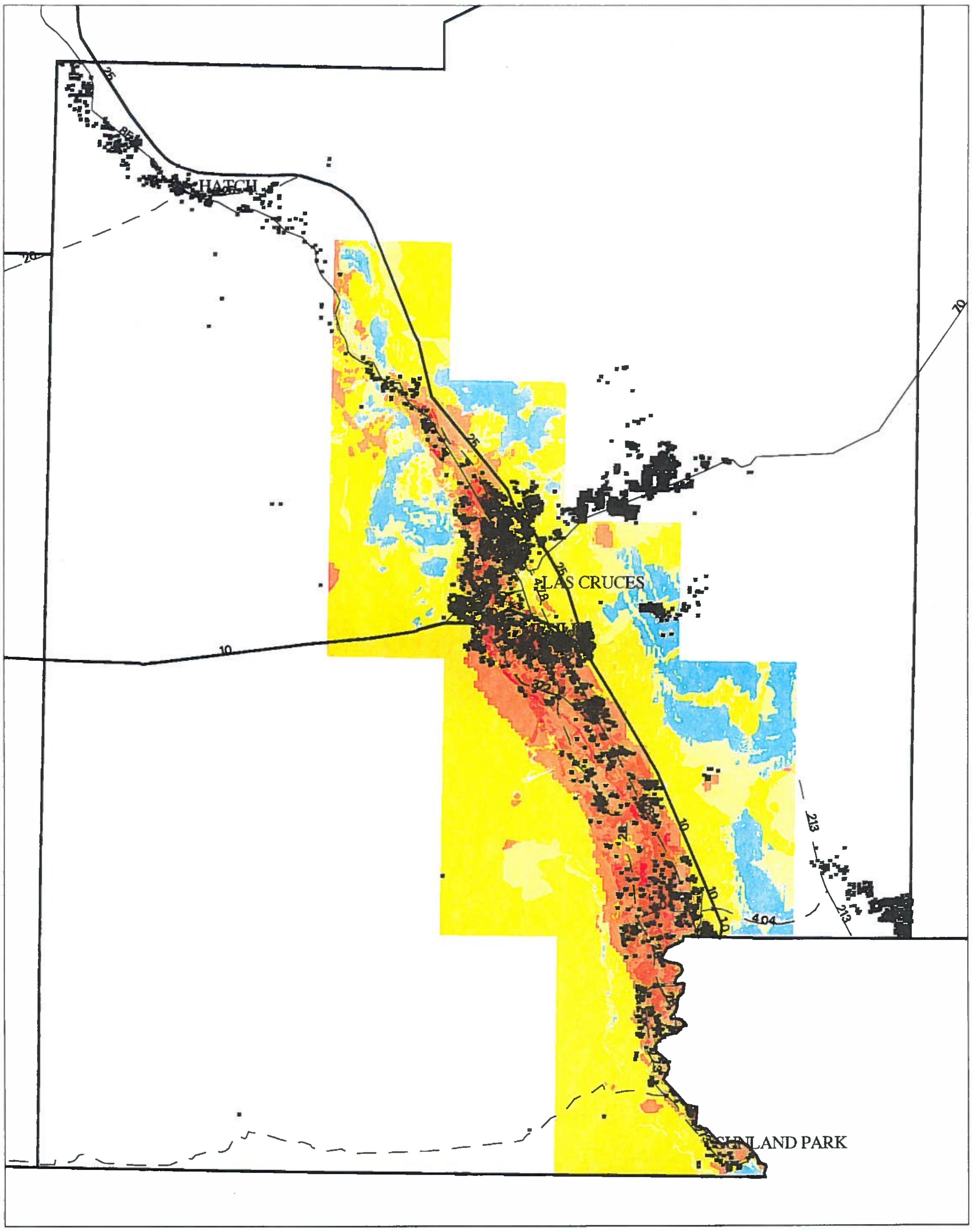
Sources of Contamination

There are two major potential sources of groundwater contamination in the Rio Grande Valley which might impact the Mesilla Bolson: agricultural activity and high density residential septic tanks. The agricultural activity can again be broadly sub-divided into two major impact categories: cropping and dairies.

Aquifer sensitivity assessment

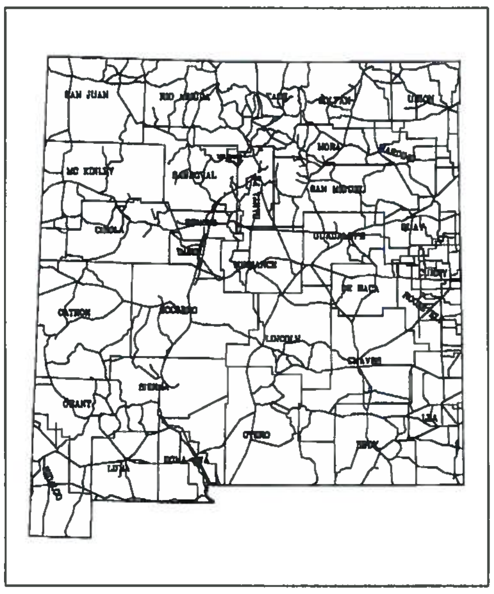
A study has been completed to assess the natural sensitivity of the groundwater aquifers in the Mesilla Valley of southern New Mexico and to assess, using a model, the potential impact that farmers' and selected irrigation scheduling practices may have on selected pesticides leaching and concentrations below the root zone (Creel and others, 1997).

This assessment of the natural sensitivity of the groundwater aquifers employed a regional Geographic Information System (GIS) to determine and map the relative sensitivity of aquifers to contamination sources. The DRASTIC model was used to assess aquifer sensitivity by combining data sets that describe the depth-to-groundwater, recharge rates, aquifer material, soils composition, land slope, vadose zone materials, and saturated hydraulic conductivity. The study evaluated the data requirements and techniques necessary to employ the DRASTIC model so that it could be utilized in other regions of New Mexico. GIS coverages were developed for each of the DRASTIC parameters and combined into a natural sensitivity coverage for the study area. The resulting natural sensitivity values were grouped into six categories: very slight - indicating that the groundwater aquifer is very well protected and risk of contamination from nonpoint sources is very low; slight - the groundwater aquifer is reasonably well protected, but because one or more of the hydrologic parameters are conducive to contaminate transport, there is a higher level of risk of nonpoint pollution; low - the groundwater aquifer is somewhat protected, but more than one of the parameters are conducive; moderate - the groundwater aquifer is susceptible to contamination because few natural protections exist; severe - the groundwater aquifer is much more susceptible to contamination due to several hydrologic conditions; and extreme - all hydrologic parameters are conducive to the rapid transport of contamination to the groundwater aquifer. Results indicated that of the 2,282 km^2 included in the study area less than one percent was classified as extreme, slightly over 10 percent as severe,



Explanation

- Septic Tanks
- Interstate
- US Highway
- State Highway
- County Line
- 🟦 VERY SLIGHT –groundwater aquifers are very well protected and risk of contamination from non point sources is very low (overall DRASTIC index less than 86).
- 🟨 SLIGHT –groundwater aquifers are reasonably well protected, but because one or more of the hydrologic parameters are conducive to contaminant transport, there is a higher level of risk of non point pollution (overall DRASTIC index from 87 to 112).
- 🟨 LOW –groundwater aquifers are somewhat protected, but more than one of the parameters are conducive to contaminant transport (overall DRASTIC index from 113 to 139).
- 🟧 MODERATE –groundwater aquifers are somewhat susceptible to contamination because few natural protections exist (overall DRASTIC index from 140 to 175).
- 🟧 SEVERE –groundwater aquifers are much more susceptible to contamination due to several hydrologic conditions (overall DRASTIC index from 176 to 200).
- 🟥 EXTREME –all hydrologic parameters are conducive to the rapid transport of contamination to the groundwater aquifers (overall DRASTIC index greater than 200).



SOURCE: Creel, B., Sammis, T., Kennedy, J.F., Sitze, D.O., Asare, D., Monger, H. C., and Samani, Z. A., Groundwater Aquifer Sensitivity Assesment and Management Practices Evaluation for Pesticides in the Mesilla Valley of New Mexico: New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, New Mexico (in press).

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SCALE 1:500000

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KILOMETERS

Figure 2.7. Septic Tanks and Natural Sensitivity of the Mesilla Valley
Dona Ana County, New Mexico

almost 19 percent as moderate, almost 43 percent as low, almost 16 percent as slight, and over 12 percent as very slight.

Cropping activity

The cropping activities which may have a negative impact on the groundwater are: fertilization practices, pesticide and herbicide use, and irrigation practices. Some examples will be used to demonstrate the magnitude of the problem. Nitrate concentrations of 10 - 40 mg/L have been reported in the shallow groundwater just below onion fields (Gallego, 1994). Fertilization in excess of plant use may move down past the root zone and go to the groundwater if it is not intercepted by a drain.

The other major inorganic agricultural contaminant of concern, besides nitrate, in both surface and groundwater is salinity. The TDS of the river water progressively increases as the Rio Grande flows toward the south (Wierenga, 1979). The increased salinity of the groundwater is due to irrigation return flow from about 400 miles of open drains installed along the agricultural fields in the Mesilla Valley and the influx of treated wastewater from municipalities. The drain ditches intercept the water table in the valley and drains the incoming seepage from agricultural fields into the Rio Grande. The drains play an important role in the quality of the groundwater by intercepting and draining the seepage water from the farms. However, drains do not intercept the entire seepage water, thus some of the seepage water replenishes the aquifer in the areas where pumping is taking place. The recharge of the aquifer by seepage water contributes to salinization of the groundwater through lateral and vertical migration of the salt. It is speculated that if the current practice of furrow irrigation was switched to drip irrigation, the quantity and quality of water seeping into the aquifer would be drastically reduced. However, there is so little baseline data available, it is difficult to quantify the magnitude of the existing flux. It is equally difficult to predict the impact of changing irrigation and fertilization practices without first having an accurate understanding of the existing situation.

Dairies

The number of milk cows in Doña Ana County in 1994 was estimated to be 31,000 (USDA, 1994). The dairy activity is largely concentrated south of Las Cruces along the eastern border of the Mesilla Bolson. There are ten dairies along an eight mile stretch between Mesquite and Vado (Figure 2.8). In terms of waste production, each cow can be viewed as the waste equivalent of 15 - 20 people. This is roughly equivalent to the waste load of 465,000 people. The wastewater from these dairies are either stored in lagoons or applied to the agricultural fields through sprinkler or conventional flood irrigation. The seepage from lagoons, corrals and agricultural fields which cover several hundred acres, all contribute to increased groundwater salinity and nitrate contamination in the area. Figures 2.9 thru 2.11 are a detailed site map, groundwater contour map, and a contamination map, respectively. It is seen that the water directly under the dairies contains nitrate concentrations in the 100 to 150 mg/L range. Jacquez and Samani (1992) measured groundwater nitrate contamination ranging from 20 to 200 ppm and salinity of more than 1,500 ppm in the groundwater under the dairies. At this time the nitrate is not moving significantly in the groundwater. The dairies production wells are containing the majority of the plume. However, in the event the dairies cease pumping water or new production wells are developed in the vicinity, the plume would be free to move downgradient and could do significant damage to adjacent groundwater. The potential mobility is illustrated by the nitrate in the Figure 2.11 which has already started to move. The nitrate that is moving to the south is nitrate associated with the treated dairy wastewater applied to irrigated fields outside of the cone of depression formed by the dairy production wells.

Septic tanks

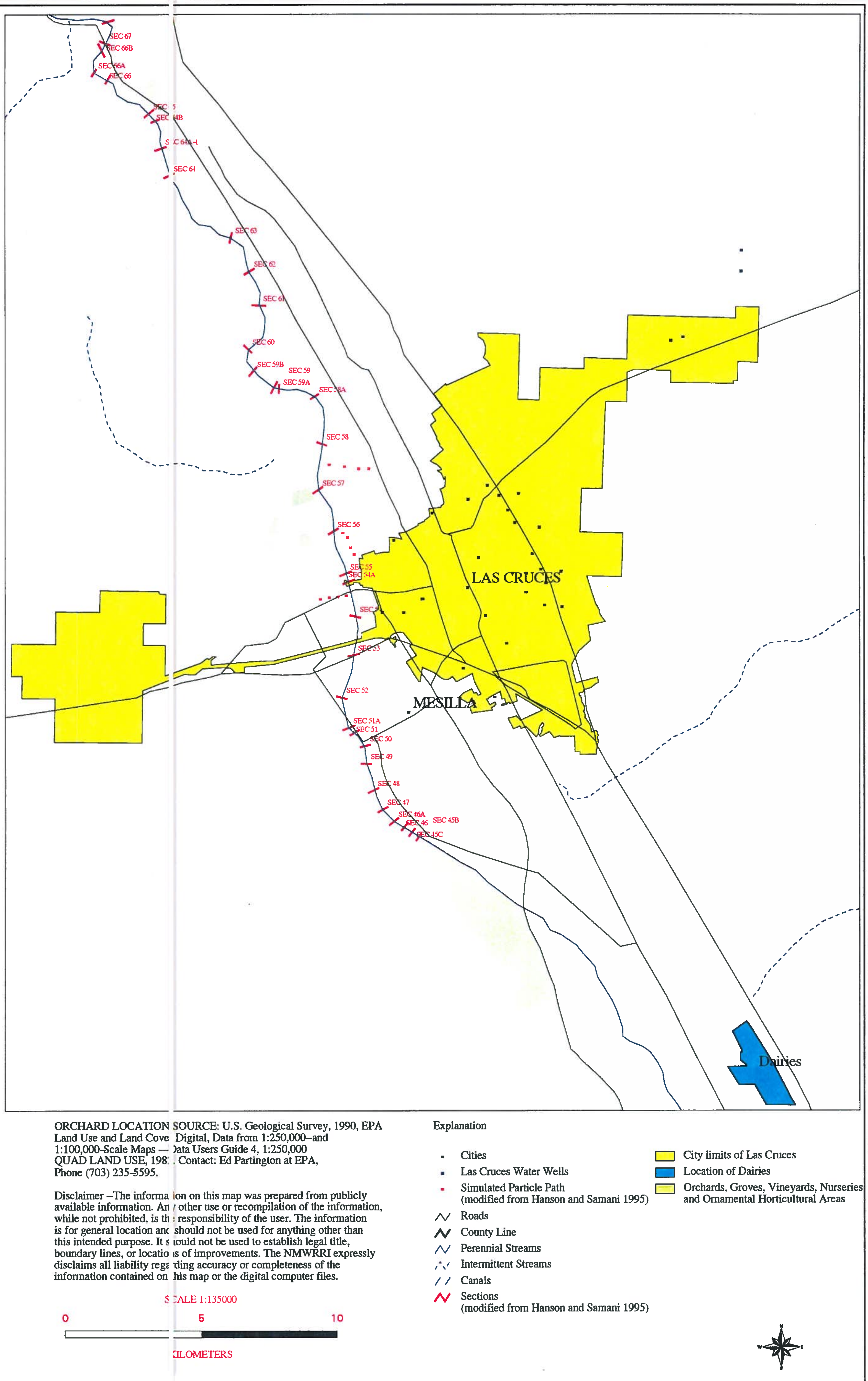
Although the nitrate levels associated with the groundwater under the dairies are significantly higher than those expected in septic tank effluent (150 mg/L vs 45 mg/L), and the volume of septic tank effluent is less than the volume of wastewater produced by the dairies. The waste produced is still very significant. It is estimated, based on figures from the 305(b) report, that the volume of waste water discharged to the groundwater may be as high as 2.2 MGD from septic tanks over the Mesilla Bolson. This represents approximately 825 lb/day of nitrogen being discharged into the subsurface environment from septic tanks over the Mesilla Bolson. Septic tanks are considered the single largest non-point source of groundwater contamination in the state of New Mexico. According to Water Quality and Water Pollution Control In New Mexico 1994, the Clean Water Act 305(b) report, more than 50 percent of the identified cases of groundwater contamination in the state of New Mexico are attributed to non-point (diffuse) sources. Most of these cases involve large numbers of small, household septic tanks and cesspools distributed over rapidly developing areas in unsewered subdivisions and un-incorporated rural areas. It is estimated that there are over 170,000 septic tanks and cesspools in the State with a subsurface discharge of 51,000,000 gallons of waste water every day (NMWQCC, 1994).

While these septic tank discharges and their impact on groundwater is a State wide problem, the areas of greatest concern are the regions associated with the Colonias, many of which are over the Mesilla Bolson. The 305(b) report (NMWQCC, 1994) referred to Colonias as one of the more serious environmental concerns facing New Mexico along its southern border. The report notes that "Congestion, uncontrolled urban development, and lack of basic environmental health and sanitation facilities have become significant problems in many communities on both sides of the border" (NMWQCC, 1994). Of the estimated 200,000 residents in El Paso County, Texas and over 40,000 residents of southern Doña Ana County, New Mexico, fewer than 7% are on sewered wastewater systems. The majority use on-site waste treatment systems.

The majority of the current Colonia residents are first and second generation, low income, migratory families of Mexican descent. In New Mexico the vast majority of the Colonias with their overwhelming concentrations of people and concurrent health and environmental concerns occur along the 44 mile stretch of the Rio Grande Valley from Las Cruces to the El Paso/Ciudad Juarez Metro area. In Doña Ana County alone, 43 percent of all dwellings in the un-incorporated areas were mobile homes according to 1990 data. Of these residents (about 40,000 people), only 20% are connected to public water supplies. This leads to serious environmental and public health concerns because the groundwater is very sensitive to environmental damage from non-point sources like septic tanks and their associated liquid disposal systems (drainfields).

This is illustrated by combining the natural sensitivity information map with the location of on-site liquid waste facilities (septic tanks) in Doña Ana County (Figure 2.7). The septic tank data was developed in 1994 by the Doña Ana County Planning Department by use of county land parcel database. Parcels that have had building permits issued or had mobile home utility connections, that were not served by a liquid waste treatment system were assumed to have on-site liquid waste facilities (septic or cesspool). The location of the on-site facility was calculated as the centroid of the parcel polygon. This database is shown as dots on the natural sensitivity map. It is seen that most of these septic tanks between Las Cruces and the Texas/Mexico Border are located in the naturally sensitive portion of Mesilla Valley.

The potential groundwater problems associated with dense septic tank development are well documented. Because of the reliance on groundwater in the arid southwest, this area is particularly vulnerable to damage. Very few of the individuals building homes in the Colonias and similar developments can afford the luxu-



ORCHARD LOCATION SOURCE: U.S. Geological Survey, 1990, EPA Land Use and Land Cover Digital, Data from 1:250,000–and 1:100,000-Scale Maps — Data Users Guide 4, 1:250,000 QUAD LAND USE, 198 . Contact: Ed Partington at EPA, Phone (703) 235-5595.

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Figure 2.8. Dairies, Particle Tracking Sections, and Orchard Location

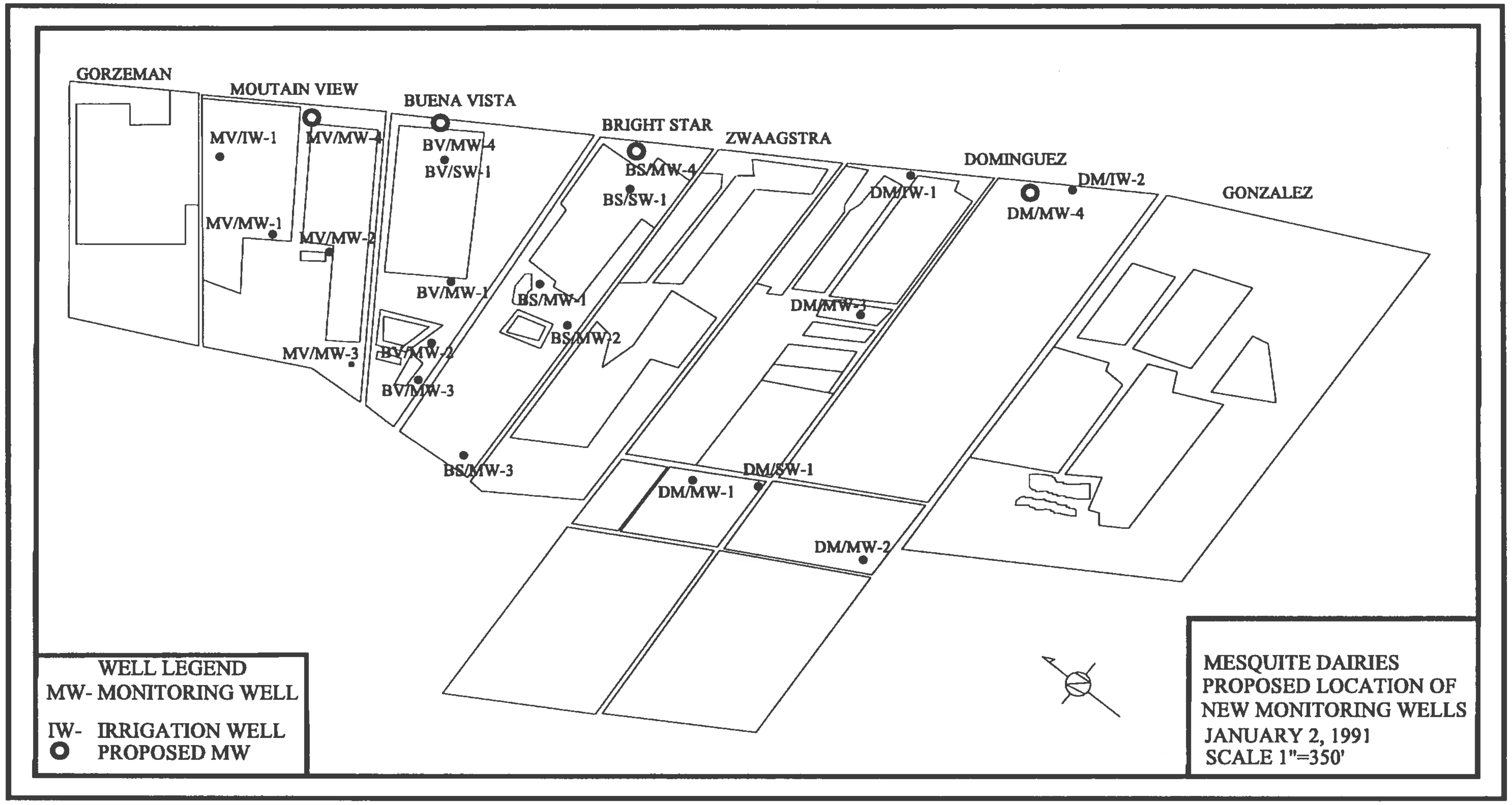

Figure 2.9. Dairy site map detail.

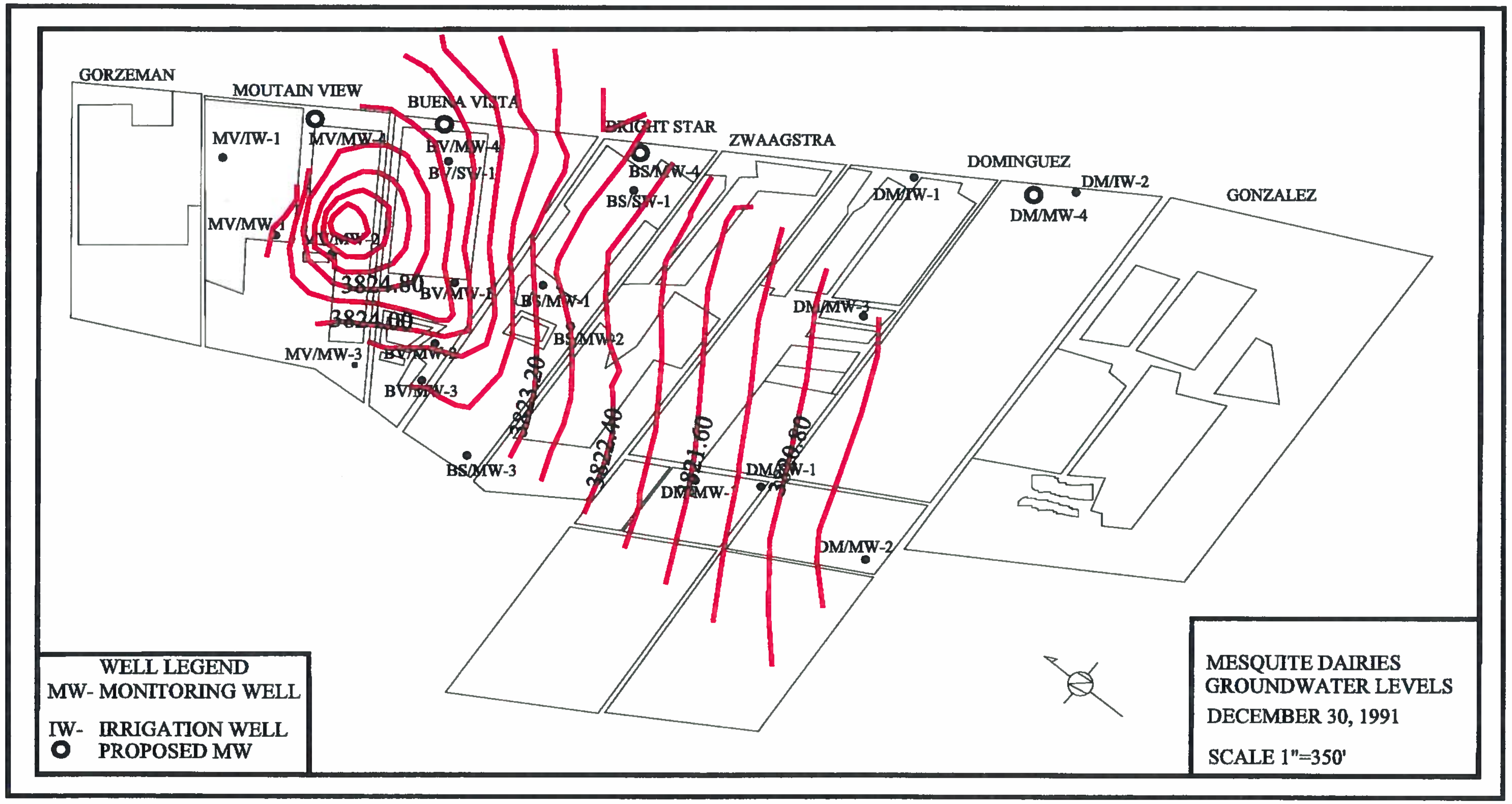

Figure 2.10. Dairy groundwater levels.

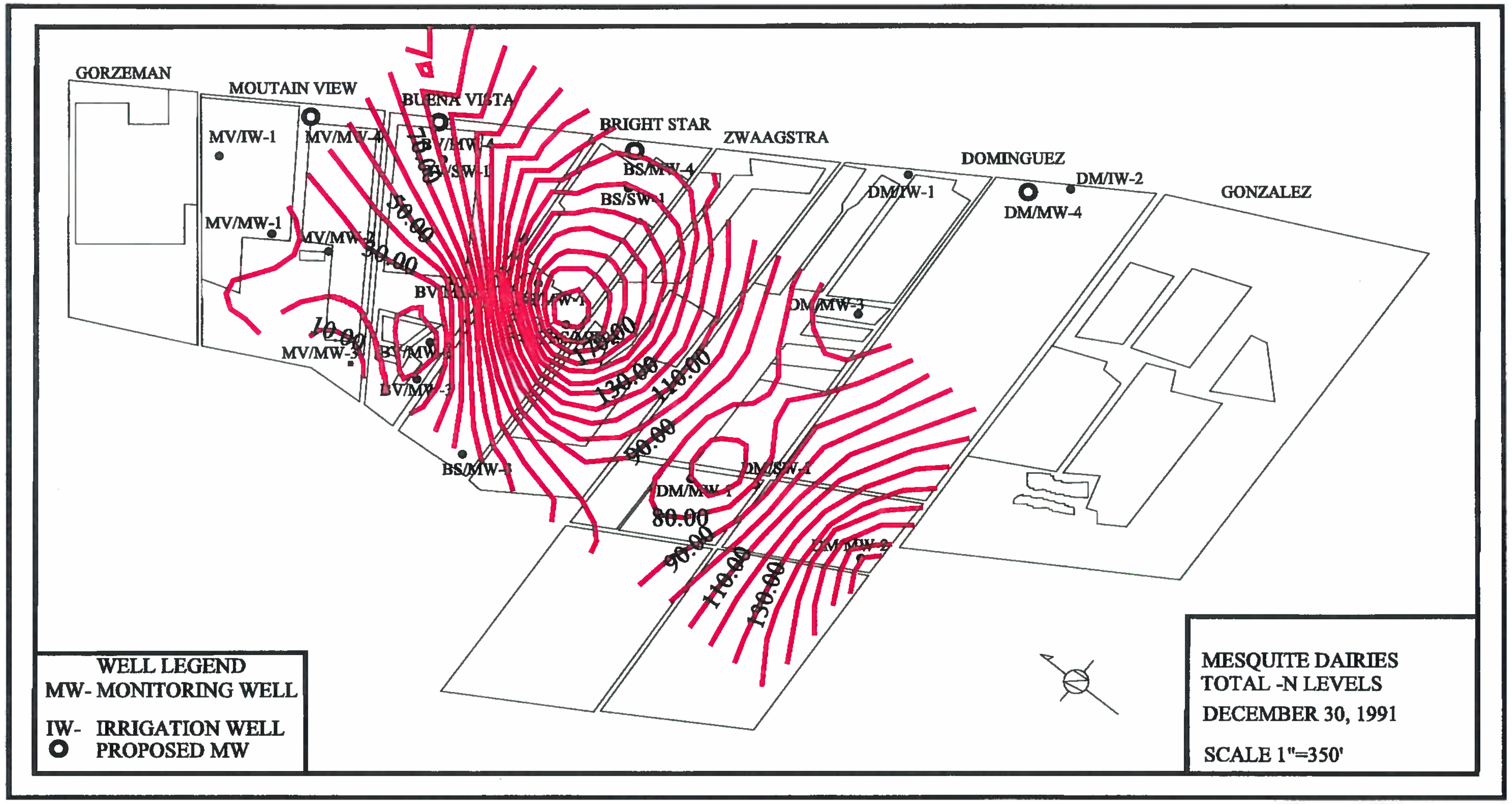

Figure 2.11. Dairy groundwater nitrate levels.

ry of hiring a contractor to install their septic tank and drainfield system. Many of the residents of Doña Ana County and El Paso Counties are extremely poor with the average annual incomes less than $9,500. While the average incomes remain low, growth is very rapid exceeding 15 percent per year in the region. The development scenario just described has caused concern among County Planning Staffs and state environmental professionals, and represents a severe threat to groundwater in the Mesilla basin aquifers. Regardless of the nitrogen form when it is discharged from the septic tank, it will eventually be converted to nitrate. There is little possibility of the nitrate being removed from the groundwater, so it will build up over time. This will become a critical problem when the groundwater levels of nitrate approach 10 mg/L, which is the Safe Drinking Water Act (SDWA) Maximum Contaminant Level (MCL) for nitrate.

Particle tracking

One means of estimating the impact of a pollution source on the aquifer is to use a particle tracking model. Particle tracking simulations have been performed in the Mesilla Bolson near Las Cruces, NM (Hanson and Samani, 1995) to evaluate the potential for contaminate migration from the Rio Grande into the adjacent aquifer. The river reach near Las Cruces was selected since the large cone of depression associated with the City well field is a worst case condition. For the Hanson and Samani (1995) study, simulated particles were released at different stations, located at the midpoint of a cross-section, from the bottom of the Rio Grande stream bed and then tracked for a period of 50 years. An overview of the cross-sections modeled is shown in Figure 2.8.

The rate and direction of particle transport from the river to the adjacent groundwater was directly related to hydraulic gradient. The simulation showed that between sections 57 and 58, which were under strong influence of the cone of depression created by the Las Cruces City Well Field, the particles moved east toward the cone of depression at a rate of 160 feet per year. Between sections 55 and 56, which were not affected by the cone of depression, the movement of the particles were parallel to the river channel. At sections 55 and 54, which were outside of the zone of municipal well field influence but were influenced by irrigation wells on the west side of the river, the simulated particles moved toward the west at a rate of 60 feet per year. It is clear from Figure 2.3 that the cone of depression for the municipal well field may have an impact on the transport of contaminants in the aquifer. The quality of the river water can have significant impact on the adjacent groundwater especially since some of the municipal wells are located less than 4,000 feet from the river.

There is evidence from water quality data collected by the City of Las Cruces that the cone of depression formed by the City's well field facilitates the vertical and lateral transport of contaminants from the agricultural area on the west side of the river, under the river and into the City well field. Particle tracking simulations were conducted by the City of Las Cruces (Gallego, 1994) to evaluate the potential for contamination of City's public water supply wells outside of the irrigated areas due to chemical application within the irrigated areas in the valley. The simulation showed that nitrate contamination in the groundwater below the agricultural fields can apparently reach and contaminate City's wells which are several miles outside of the agricultural areas along the interstate I-10. The results of this simulation were confirmed by actual measurement of elevated nitrate levels within the modeled wells.

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CHAPTER 3 - HUECO-TULAROSA AQUIFER

Location and Extent

The Tularosa Basin extends northward for 170 mi from south-central New Mexico to a gentle surface divide about 7 mi 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 Doña Ana and Otero Counties, New Mexico (Figure 3.1), which includes 2,600 mi^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 Juarez to the west and to the Sierra El Presidio and Sierra Guadalupe to the south. From the Sierra Juarez, 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 chapter.

Total surface area of the portion of the Hueco-Tularosa aquifer evaluated in this chapter is 4,160 mi^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 Juarez, and for military installations and smaller cities in New Mexico and Texas.

Stratigraphy and Water-Bearing Characteristics

Basin geometry

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 (Figure 3.2). From the New Mexico/Texas State line to the international border, the asymmetric shape of the basin and basin fill thickness remain fairly constant (Figure 3.3). Hydrogeologic cross sections show basin fill thickening and inferred geology at three transects across the basin (Figure 3.4). Basin fill thickness increases from a maximum thickness of 3,800 ft at Section A - A' to a maximum thickness of 9,000 ft at Section C - C' (Figure 3.4).

Rock and sediment types

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 consist mostly of Permian and Cretaceous carbonate rocks and some Tertiary intrusive rocks. The Sierra Juarez, 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, heterogeneous materials that overly Precambrian through Tertiary rocks (Sandeen, 1954; 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. Lacustrine deposits predominate in the center of the Tularosa Bolson and may correlate to the Fort Hancock deposits in the Hueco and Mesilla Bolsons (Strain, 1966). Gypsum playa deposits are found at Alkali Flat and in earlier deposits that now underlie the White Sands area.

Fort Hancock deposits south of the New Mexico/Texas State line include lacustrine muds, interbedded with layers of bentonitic claystone and siltstone and some discontinuous sand lenses. Overlying the Fort Hancock Formation is the Camp Rice Formation, a Pliocene unit that consists of stream-channel and floodplain deposits. Camp Rice deposits are juxtaposed against fanglomerates that flank the margin of the basin (Strain, 1966). Deposits in the Camp Rice Formation include predominantly gravels and sands, interbedded with muds, volcanic ash, and caliche (Wilkins, 1986). Sand and gravel sediments in the Camp Rice Formation are thickest along the Franklin and Organ Mountains, becoming thinner and finer-textured to the east (USBR, 1973). Highly permeable bolson sediments are not abundant near the Hueco Mountains (USBR,1973). Throughout the basin, the percentage of clay increases generally with depth (Orr and Risser, 1992).

These same general trends are shown by the electrical resistivity cross section D - D' in Mexico (Figure 3.5). 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 150 to 650 ft of bolson fill, probably Camp Rice equivalent deposits (Figure 3.5). The high resistivity values suggest potable waters are present in relatively coarse-textured sediments. At depths between 800 and 1,600 ft, the electrical resistivity values are usually less than 15 ohm-m. Such low values imply clay-dominated strata, perhaps Fort Hancock deposits, 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 2,000 to 2,500 ft, 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 650 ft 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 3.5). An exception is between G5A and D' where a 160 ft 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 Arroyo (Geo Fimex, 1970).

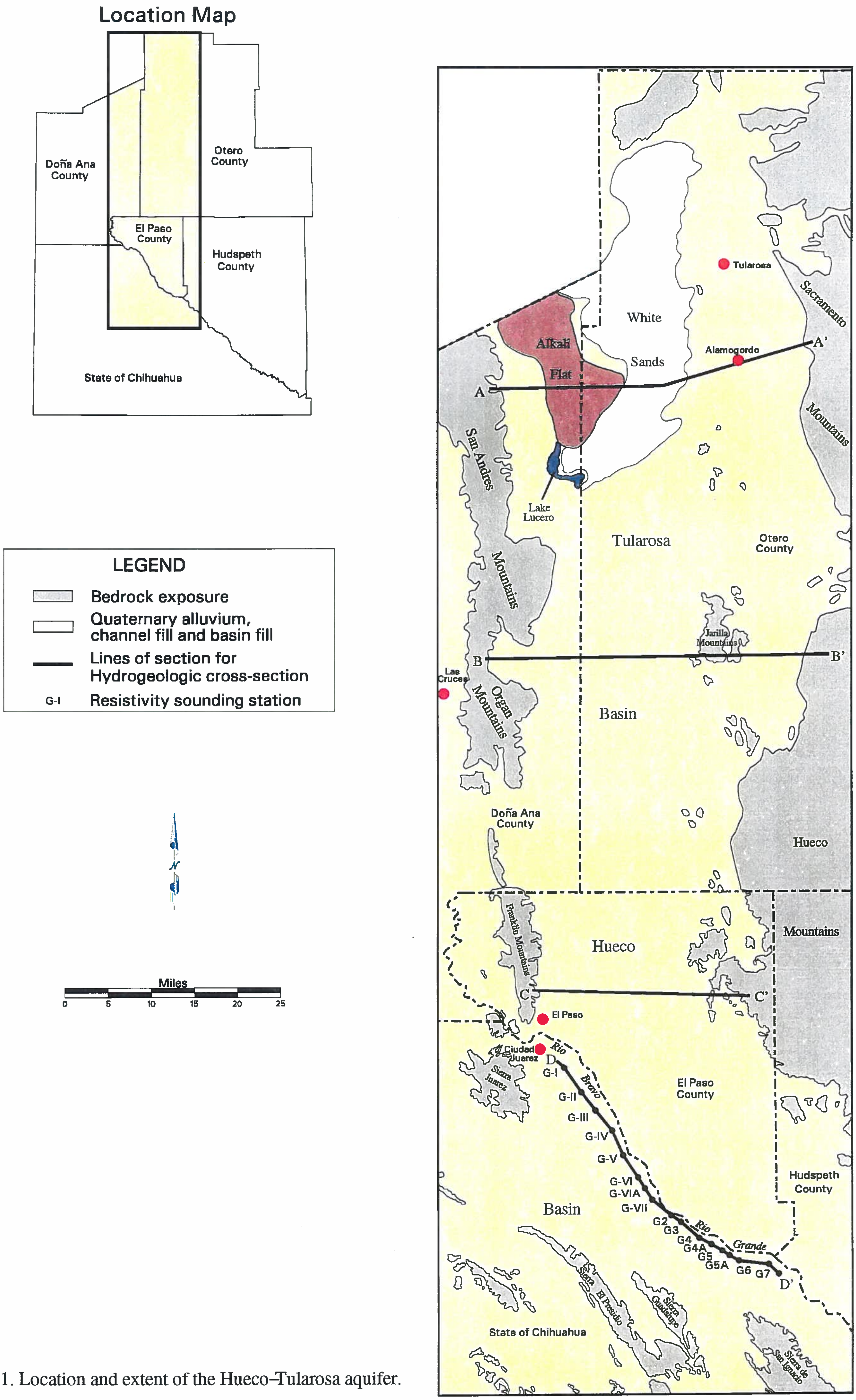


Figure 3.1. Location and extent of the Hueco–Tularosa aquifer.

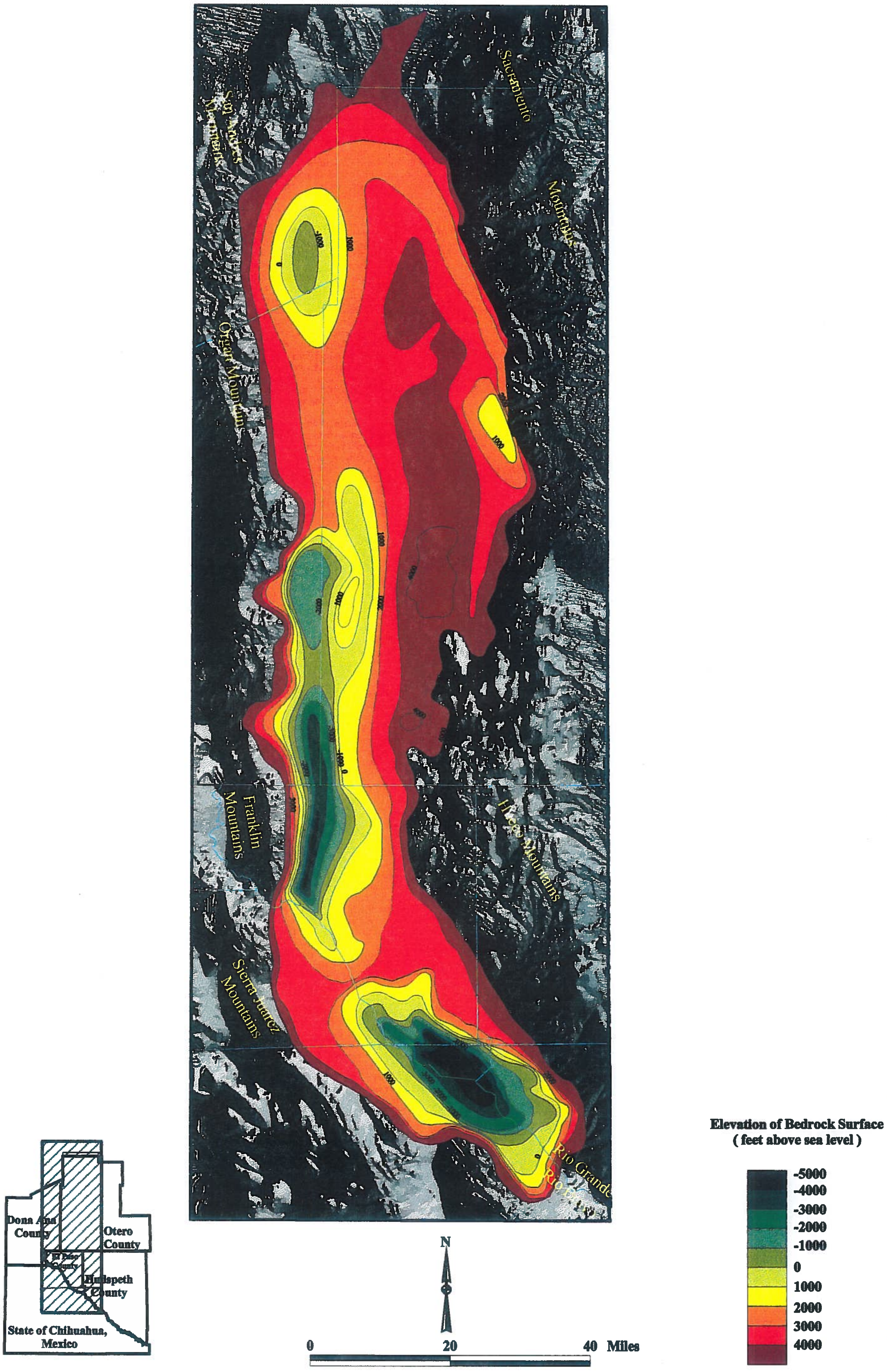


Figure 3.2. Bedrock configuration map beneath the Hueco and Tularosa Bolsons (source, Davis and Legatt, 1967; McLean, 1970; Lee Wilson and Associates, 1986; Collins and Raney, 1991; map prepared by E. Boghici).

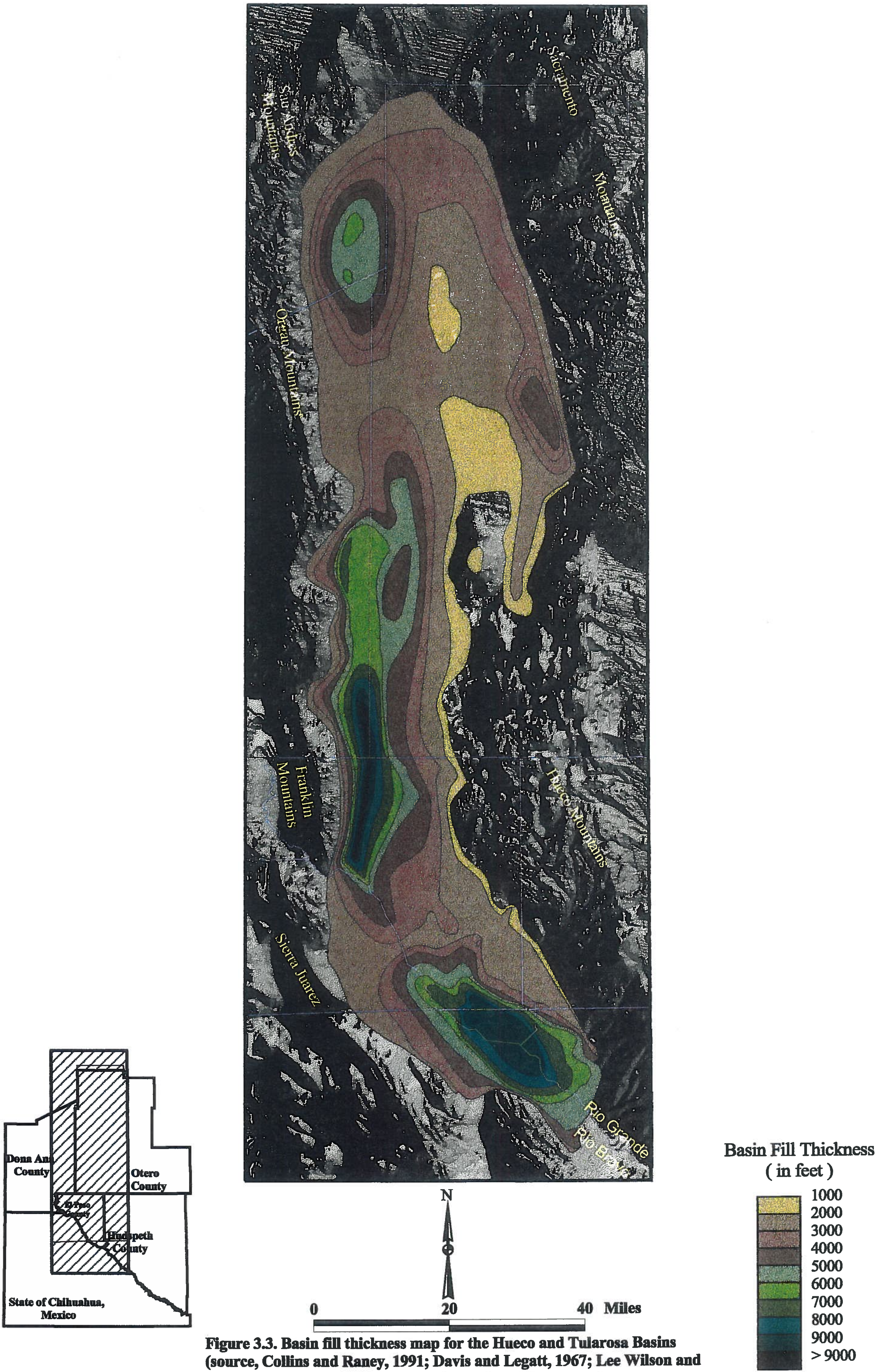


Figure 3.3. Basin fill thickness map for the Hueco and Tularosa Basins (source, Collins and Raney, 1991; Davis and Legatt, 1967; Lee Wilson and Associates, 1986; McLean, 1970; map prepared by E.Boghici).

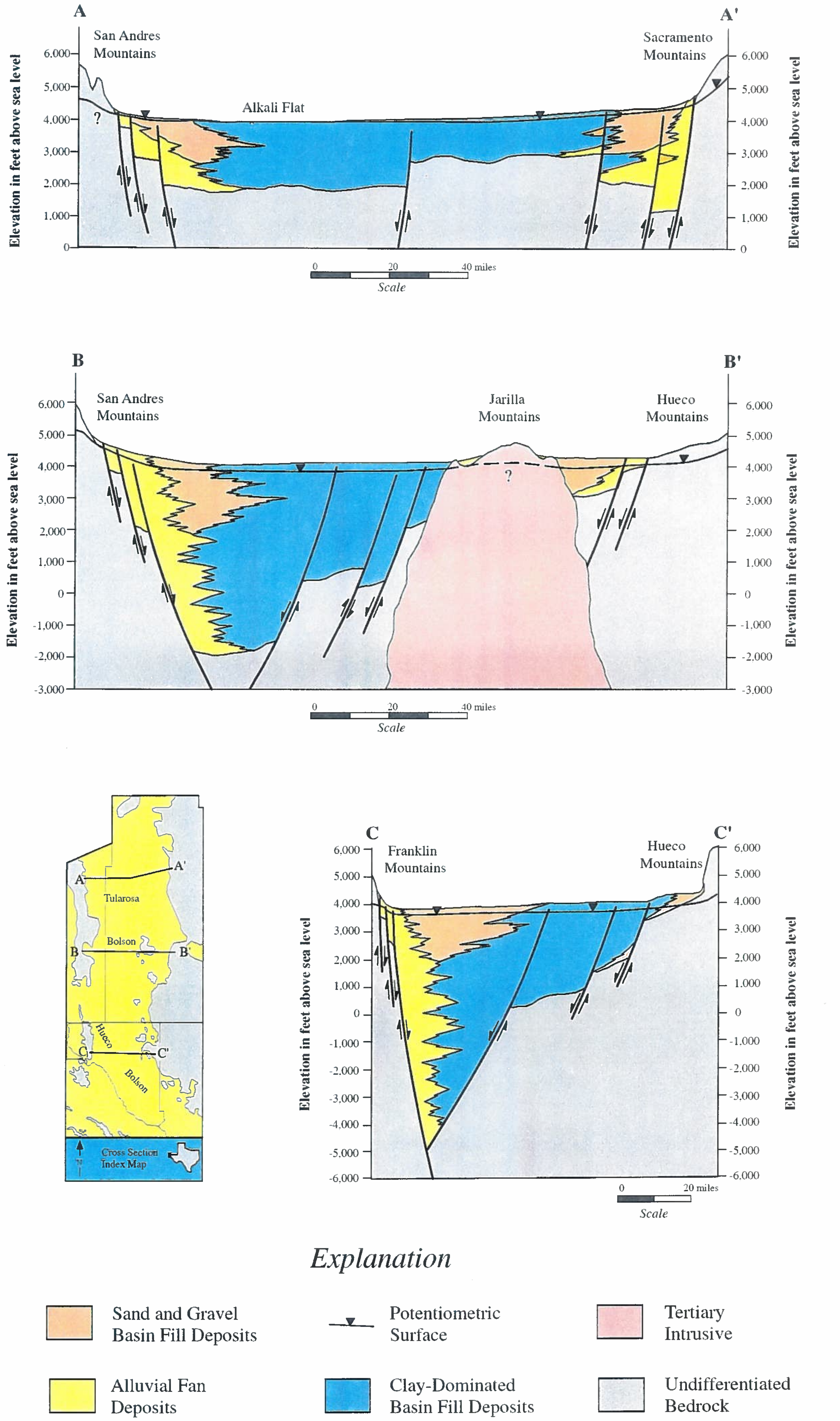


Figure 3.4. Geneneralized hydrogeologic cross sections A - A', B - B', and C - C' across the Hueco-Tularosa aquifer (Basin fill/bedrock contacts selected from maps prepared by Davis and Legatt, 1967; McLean, 1970; and Lee Wilson and Associates, 1986. Cross section C - C' modified from Lee Wilson and Associates, 1986).

Geoelectric Cross Section D - D' - Juarez Valley, Chihuahua, Mexico

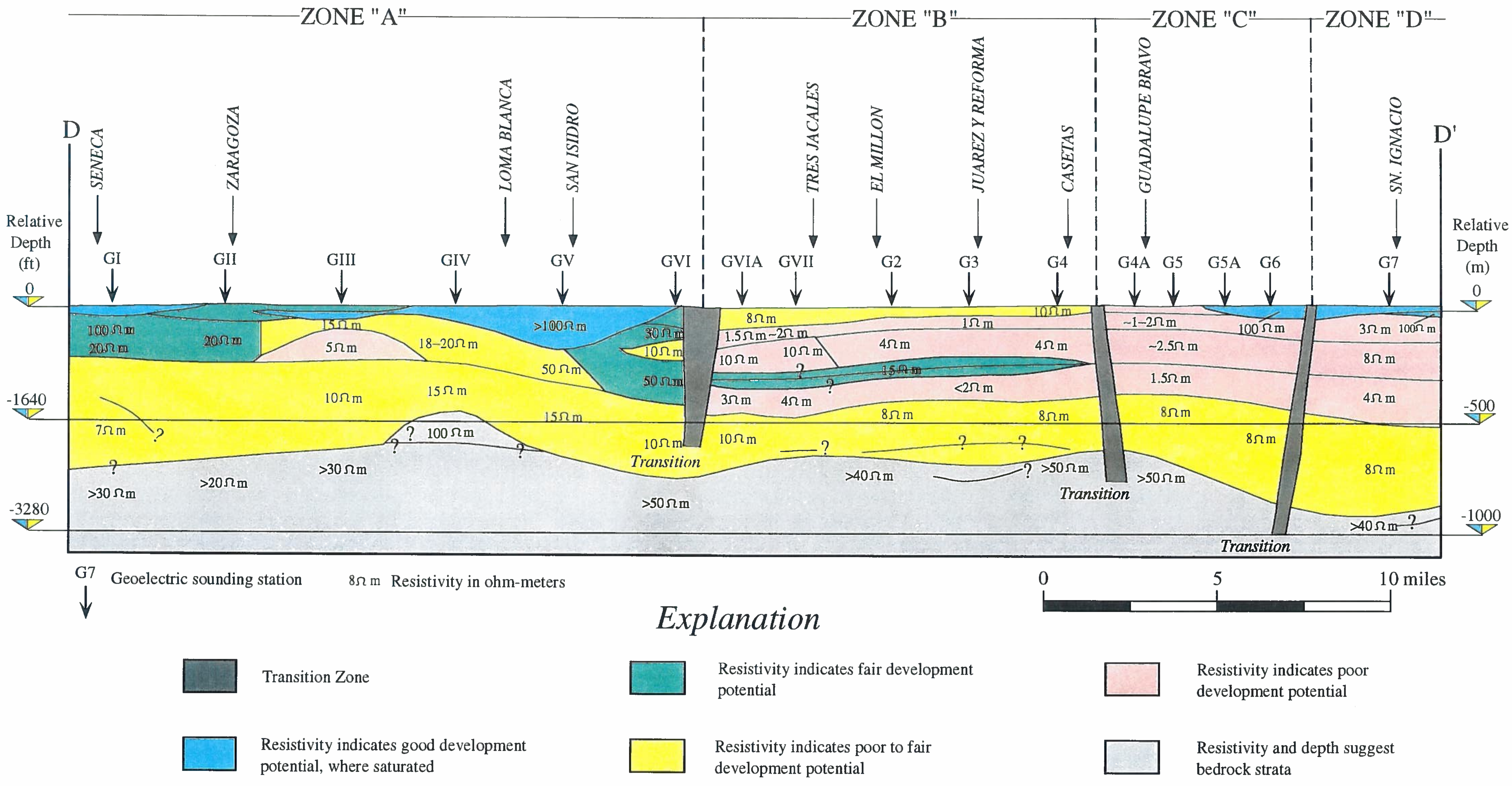


Figure 3.5. Geoelectric cross section D - D' across the Hueco-Tularosa aquifer, northern Chihuahua, Mexico. The map shows interpreted average real resistivities (modified from Geo Fimex, 1970; line of section shown on Figure 3.1).

Aquifer properties

Well yields in the New Mexico part of the Hueco-Tularosa aquifer vary greatly. Most of the wells produce water from alluvial fans that flank the mountains (Orr and Myers, 1986). Well yields of 1,400 gpm are reported at elevations high on the fans decreasing to 300 to 700 gpm at the lower edges of the fans (McLean, 1970). Well yields in the mud-rich sediments toward the center of the Tularosa Bolson are usually less than 100 gpm and sometimes less than 15 gpm (Wilkins, 1986).

Consolidated rock aquifers beneath the mountains, and alluvial fans that flank the highlands generally contain the only potable ground water in the New Mexican part of the Hueco-Tularosa aquifer (Herrick and Davis, 1965; McLean, 1970). The freshwater areas are underlain by saline water at depth. The thickness of the freshwater water lense thins to a feathers edge basinward of the alluvial fans. Few wells are present along the low lying areas of the Tularosa Basin because ground waters beneath the basin floor are not potable generally.

Most of the aquifer test data are from the western part of Hueco-Tularosa aquifer (Lee Wilson and Associates, 1986; Orr and Myers, 1986). Transmissivity estimates at the western part of the Tularosa Basin were derived from aquifer tests in alluvial fans primarily. Transmissivity estimates are available mostly for the Soledad Canyon re-entrant and adjacent areas. A few values are available for White Sands re-entrant. Transmissivity estimates on the west side of the basin vary from 160 to 79,000 ft^2/day (Orr and Myers, 1986).

Aquifer tests indicate that the water bearing strata have large ranges of transmissivity and hydraulic conductivity, especially in the Tularosa Bolson (Figures 3.6 and 3.7). Variable saturated thicknesses and variations in sorting and grain size account for variability of aquifer parameters (Orr and Myers, 1986). The variability of heterogeneity is controlled mostly by the heterogeneous deposition of muds, sands, and gravels; by the degree of sediment sorting (usually poor); and by basinward "sieving" along arroyos and drainage areas. Coarse-textured sand and gravel deposited at elevations high in alluvial fans are succeeded by sands and muds at the basinward edges of the fans due to lower transport energies closer to the valley floor. The percentage of sand in alluvial fan material reportedly varies from 12 to more than 95 percent on the western side of the Tularosa Basin (Orr and Myers, 1986). Sand percentages decrease basinward of the flanking highlands.

On the eastern side of the basin, ground-water data are available primarily from wellfields at Holloman Air Force Base, the City of Alamogordo, and irrigated regions near the City of Tularosa. Transmissivity data from 7 aquifer tests were located for this region and values range from 400 to 5,000 ft^2/day. McLean (1970) indicated that transmissivities in the alluvial fan material on the eastern side of the basin may range up to 20,000 ft^2/day along the mountain front, but these higher values were not found in the published literature. Most ground-water development and well test information on the east side of the basin are poorly documented (Orr and Myers, 1986).

South of the New Mexico/Texas State line, well yields in the alluvial fan and Camp Rice deposits east of the Franklin Mountains yield as much as 1,800 gpm (Wilkins, 1986). Transmissivity values in wells along the northern part of El Paso County vary typically from 4,000 to 28,000 ft^2/day. Fresh water deposits underlying the central and southern part of the City of El Paso have transmissivity values that vary typically from 4,000 to 15,000 ft^2/day. Yields from these wells are 500 to 800 gpm (IBWC, 1989). Wells underlying Ciudad Juarez yield from 300 to 1,500 gpm (IBWC, 1989). Transmissivity values of the Hueco Bolson underlying Ciudad Juarez vary from 14,000 to 24,000 ft^2/day (IBWC, 1989). The storage coefficient of the Hueco Bolson has been measured in the range of 0.093 to 0.000286 (Lee Wilson & Associates, 1986).

Published hydraulic conductivity values derived from 37 aquifer tests in the Tularosa Bolson vary from 1.0 to 320.0 ft/day (Figure 3.7). Most values are between 4.0 and 63.0 ft/day. Ranges illustrate the heterogeneity of alluvial fan sediments. Published hydraulic conductivity values derived from 73 aquifer tests in the Hueco Bolson vary from 6.4 to 98.9 ft/day (Figure 3.7). The range is smaller in the Hueco Bolson and follows a slightly skewed log probability distribution (almost log normal).

Comparison of hydraulic conductivity values between the Tularosa and Hueco Bolsons suggest more homogeneous aquifer strata in the Hueco Bolson (Figure 3.7). Wells in the Hueco Bolson are installed primarily in Camp Rice deposits, a moderately sorted, mostly fluvial deposit. The alluvial fan deposits in New Mexico have a much wider range of hydraulic conductivity due to poor sorting and extreme heterogeneity. Equivalent Camp Rice deposits in the Tularosa Bolson either do not exist or are saturated with saline ground waters and are not developed.

Potentiometric Surface Map and 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 3.8). Hydraulic head exceeds 4,400 ft along the Sacramento Mountains and defines areas of mountain front recharge. Hydraulic head exceeds 4,100 ft and hydraulic gradients are about 0.04 along the White Sands re-entrant, a narrow gap between the Organ and San Andres Mountains. White Sands re-entrant is a less prolific recharge area.

Along the basin floor, the hydraulic gradient is extremely 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 Basin into the Hueco Basin and eventually moves into Texas across the New Mexico/Texas 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 Juarez have reversed the natural hydraulic gradient. These cones of depression have created an artificial ground-water divide just north of the Rio Grande (Figure 3.8).

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 20 and 150 ft. Drawdowns in many municipal wells, up to 100 ft, have been recorded in this area (Figure 3.9). 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 400 ft. Little drawdown has been recorded there (Figure 3.9). Drawdowns in the Hueco Bolson near the New Mexico/Texas State line has been relatively small, not exceeding 5 - 30 ft. Depth to ground water in this area is about 300 - 350 ft.

South of the New Mexico/Texas State line, drawdowns since 1940 are up to 150 ft. Pumping cones of depression in municipal wellfields are the focal points of drawdown. Most of the drawdowns near municipal wellfields vary from 50 to 100 ft (Figure 3.9). Some of the highest rates of drawdown have occurred beneath Ciudad Juarez; for example, over 100 ft of drawdown has been recorded at JMAS-15 in less than 25 years (Figure 3.9). Steep rates of decline are shown for most of the other municipal wells in Ciudad Juarez. A drawdown map computed with water-level data collected

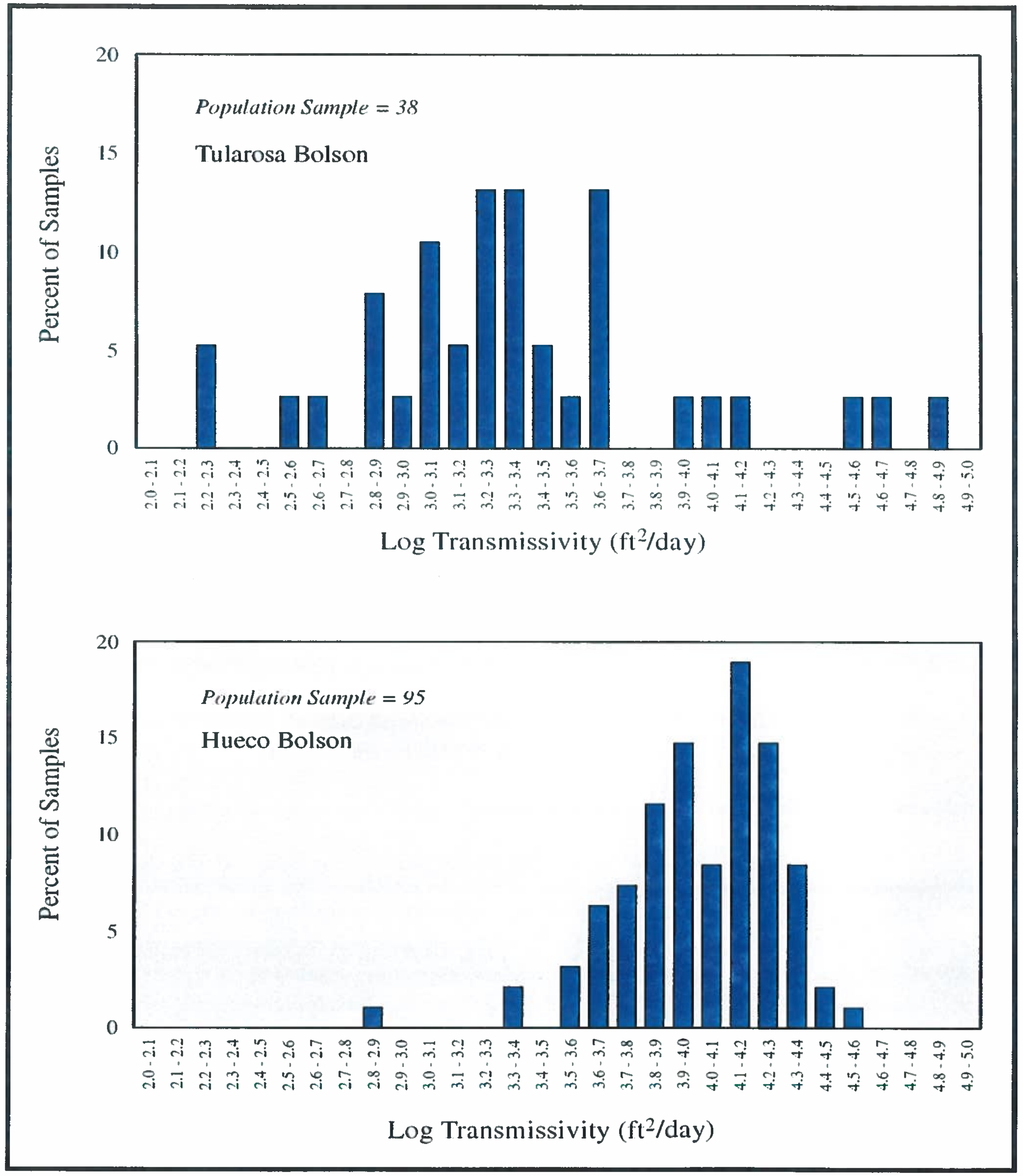


Figure 3.6. Comparison of transmissivity values derived from aquifer tests in the Tularosa and Hueco Bolsons (source of data, Kelly and Hearne, 1976; Lee Wilson and Associates, 1986; Orr and Myers, 1986).

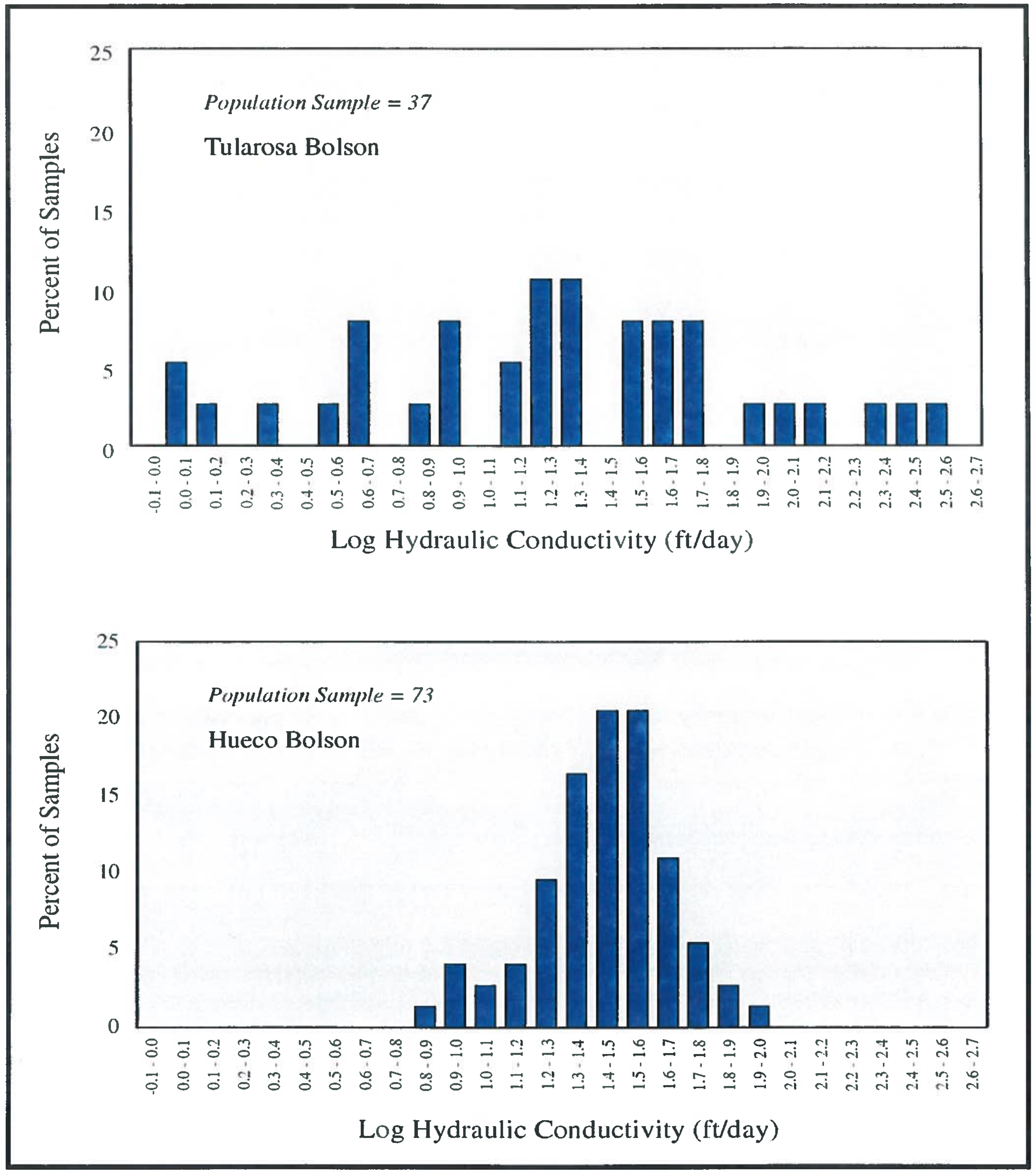


Figure 3.7. Comparison of hydraulic conductivity values derived from aquifer tests in the Tularosa and Hueco Bolsons (source of data, Kelly and Hearne, 1976; Lee Wilson and Associates, 1986; Orr and Myers, 1986).

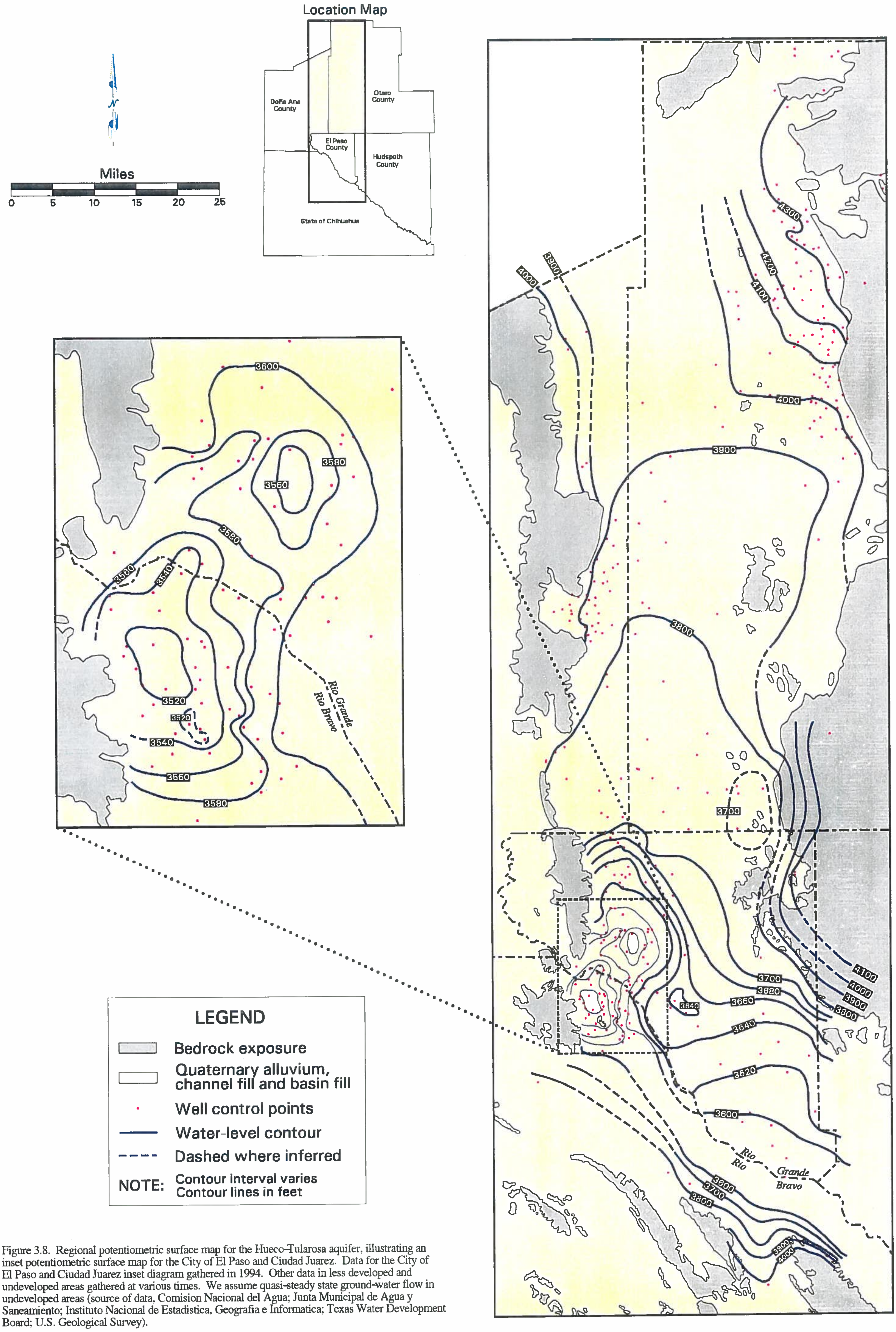
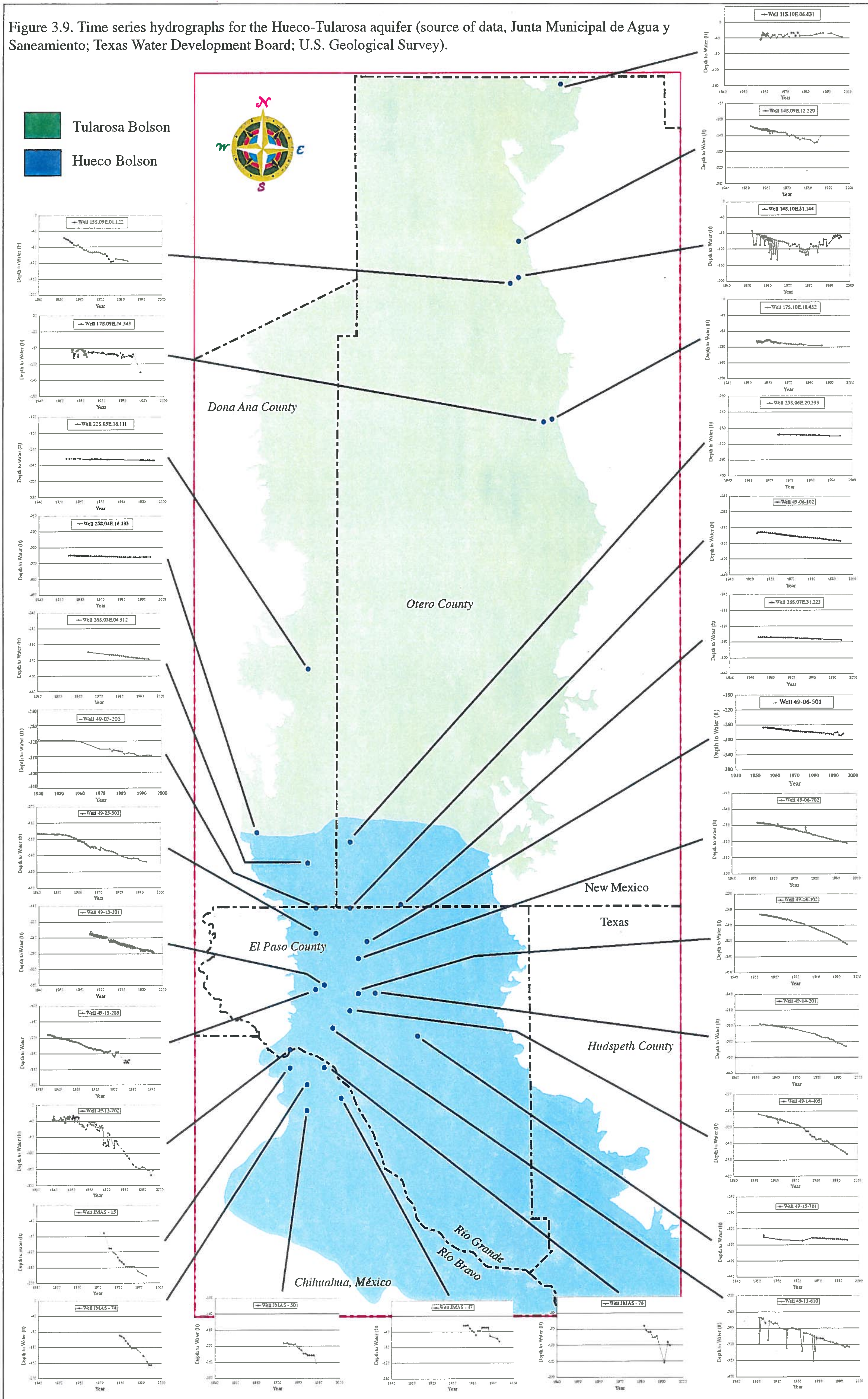


Figure 3.8. Regional potentiometric surface map for the Hueco–Tularosa aquifer, illustrating an inset potentiometric surface map for the City of El Paso and Ciudad Juarez. Data for the City of El Paso and Ciudad Juarez inset diagram gathered in 1994. Other data in less developed and undeveloped areas gathered at various times. We assume quasi-steady state ground-water flow in undeveloped areas (source of data, Comision Nacional del Agua; Junta Municipal de Agua y Saneamiento; Instituto Nacional de Estadistica, Geografia e Informatica; Texas Water Development Board; U.S. Geological Survey).

Figure 3.9. 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).



between 1987/1988 and 1992/1993 presents drawdowns in the Hueco Bolson beneath the City of El Paso and Ciudad Juarez (Figure 3.10). Focal points of drawdown are shown beneath both cities.

Ground-Water Availability

Several ground-water availability studies have been conducted to estimate the amount of recoverable fresh and slightly saline ground water in the Hueco-Tularosa aquifer. Calculations require an estimate of the volume of saturated sediments, both fresh and slightly saline, and an estimate of the specific yield of the sediments. Recoverable resources are computed by multiplying the specific yield by the volume of fresh or slightly saline ground waters. Historical estimates of recoverable resources in the Hueco-Tularosa aquifer (mostly bolson material) include (compiled by Lee Wilson and Associates, 1986):

- The Hueco Bolson in Texas contains 7,400,000 acre-ft of recoverable ground water with less than 250 mg/L Cl (about 750 mg/L TDS). The quantity of recoverable ground water in New Mexico is 6,200,000 acre-ft (Knowles and Kennedy, 1956).

- The quantity of freshwater in the Hueco Basin in New Mexico (including the western part of the Tularosa Basin) is about 17,000,000 acre-ft (McLean, 1970).

- Recoverable storage of freshwater in the Texas part of the Hueco Bolson is estimated to total about 10,640,000 acre-ft; another 4,000,000 acre-ft is potentially recoverable from the Mexican part of the Hueco Bolson (Meyer, 1976).

- The Texas segment of the Hueco Bolson contains 9,950,000 acre-ft of recoverable fresh water (<1,000 TDS) and 110,000 acre ft of slightly saline water (TDS between 1,000 and 1,500 mg/L). An additional 4,000,000 acre-ft of ground water in storage with TDS between 1,000 and 3,000 mg/L is theoretically recoverable (White, 1987).

White's (1987) estimates were derived for the year 1980. Between 1981 and 1991, approximately 990,000 acre-ft of mostly freshwater was pumped from the Texas portion of the Hueco Bolson by military bases and by the City of El Paso. Using an estimated recharge rate (natural and artificial) of between 10,000 and 14,000 acre-ft/year during this time frame (Meyer, 1976; Orr and Risser, 1992; USEPA, 1995), the remaining volume of fresh ground water in storage in the Texas portion of the Hueco Bolson at the end of 1991 was about 9,100,000 acre-ft; although, perhaps an additional 100,000 - 150,000 acre-ft was captured from the Texas part of the Hueco Bolson by Ciudad Juarez and other ground-water pumpers in Texas and Mexico. Information is lacking to make similar estimates in the Mexican part of the Hueco-Tularosa aquifer.

Using numerical models and projected pumping rates, Meyer (1976) predicted that 7,400,000 acre-ft of freshwater would be available in the Texas portion of the Hueco Bolson in the year 2020. Knowles and Alvarez (1979) used Meyer's model and higher projected pumping rates and predicted the amount of freshwater remaining in storage would be about 5,600,000 acre-ft. Conversion to surface water, conservation and water recycling and reuse, and exploitation of other ground-water basins may be required for these estimates not to be met or exceeded (Ashworth, 1990).

Recharge Areas

Recharge to the New Mexican part of the Hueco-Tularosa aquifer is mostly by mountain front recharge along the mountains that flank the highlands. Mountain front recharge occurs at ephemeral streams and arroyos that are incised in bedrock and alluvial fans around the perimeters of bolsons (Figure 3.11). Ephemeral streams have steep gradients in mountains that slope gradually where the ephemeral channels overlie alluvial fans. Some recharge occurs directly on mountain surfaces. Recharge is ordinarily greater on the alluvial fans except where calcic zones are well developed in soil profiles in the fan sediments (Hibbs and Darling, 1995). These zones impede infiltration and act as surfaces for runoff across the broad alluvial fans. Mountain surfaces can be a more prominent recharge area where calcic zones are well developed in alluvial fans. Alluvial fans formed by erosion of carbonate rocks have well developed calcic zones, whereas fans formed from erosion of crystalline intrusive and extrusive and metamorphic rocks have moderately-to-poorly developed calcic horizons (Darling and others, 1994). Infiltration rates and storage are usually lower in crystalline and metamorphic rocks, which accentuates surface runoff and recharge at the fans.

Most of the mountain and mountain front recharge occurs from widespread winter frontal systems of low intensity and long duration. High-intensity and localized thundershowers during the summer months produce short duration flows and limited recharge (Wilkins, 1986). Precipitation recharge is usually absent along basin floors due to the substantial excess of evapotranspiration over precipitation, and great depth to ground water. Fine textured soils and caliche line sediments on the basin floor and impede infiltration along drainages and dry playas.

Recharge to the Texas and Mexican parts of the Hueco-Tularosa aquifer is by mountain and mountain front recharge and by cross-formational flow from the Rio Grande alluvium. Other sources of recharge include interbasin ground-water flow from the Tularosa Bolson to the Hueco Bolson, underflow from the Mesilla Bolson through Fillmore Pass, and wastewater injection at the Fred Harvey wastewater treatment plant (Figure 3.12).

Mountain front recharge is mostly along the Franklin Mountains on the American side of the bolson and along the Sierra Juarez, Sierra El Presidio, and Sierra Guadalupe on the Mexican side of the bolson.

Recharge from the Rio Grande alluvium occurs where pumping cones of depression have reversed the natural hydraulic gradient between the Hueco Bolson and the alluvium along the Chamizal zone. Where the Rio Grande channel is lined with low-permeability grout along the Chamizal zone, the alluvium recharges the Hueco Bolson at the expense of its own storage. Where the Rio Grande is not lined the alluvium, in turn, is replenished by infiltration of river water.

Total recharge to the Hueco-Tularosa aquifer is not easy to estimate. Meinzer and Hare (1915) estimated that recharge to the Tularosa Basin exceeds 100,000 acre-ft/year. This estimate is probably excessive. Much of the older literature assumed that recharge to the desert basin is a significant percentage of the precipitation falling on mountain drainage areas. Sayre and Livingston (1945) for example, estimated that mountain front recharge to the Hueco Bolson is approximately 25% of precipitation falling on mountain and mountain front surfaces. More recent studies, bolstered by environmental isotopes and numerical models, indicate that recharge along mountains and mountain fronts is a smaller percentage of precipitation falling on mountain drainage areas; perhaps 1 to 3% (Kelly and Hearne, 1976; Orr and Risser, 1992).

Model studies predicted that 5,600 acre-ft/year comes from mountain front recharge to the Hueco Bolson (Meyer, 1976). Model analysis indicated that the recharge from the Rio Grande alluvium to the Hueco Bolson was 33,278 acre-ft/year between 1968 and 1973 (White, 1987). Lining of the Rio Grande channel in 1973 along the Chamizal zone with a low permeability grout reduced recharge by the Rio Grande significantly. Simulated recharge from underflow from the Tularosa Basin is about 3,700 acre-ft/year (Orr and Risser, 1992). Simulated recharge from underflow through Fillmore Pass is about 260 acre-ft/year (Orr and Risser, 1992).

The injection of treated wastewater at the Fred Harvey Wastewater Treatment Plant provides a limited

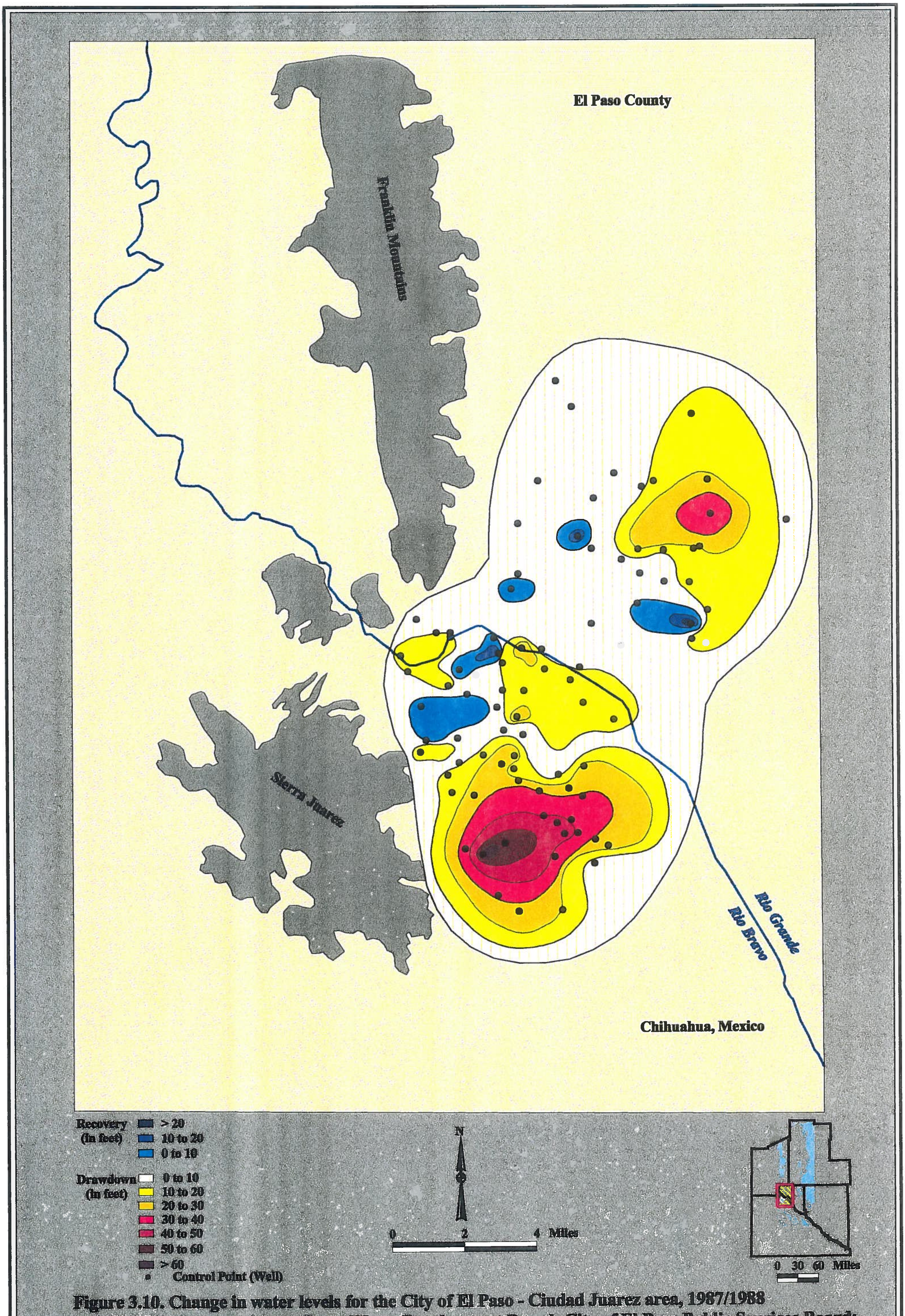


Figure 3.10. Change in water levels for the City of El Paso - Ciudad Juarez area, 1987/1988 to 1992/1993. (source of data, Texas Water Development Board; City of El Paso Public Services Board; Junta Municipal de Agua y Saneamiento).

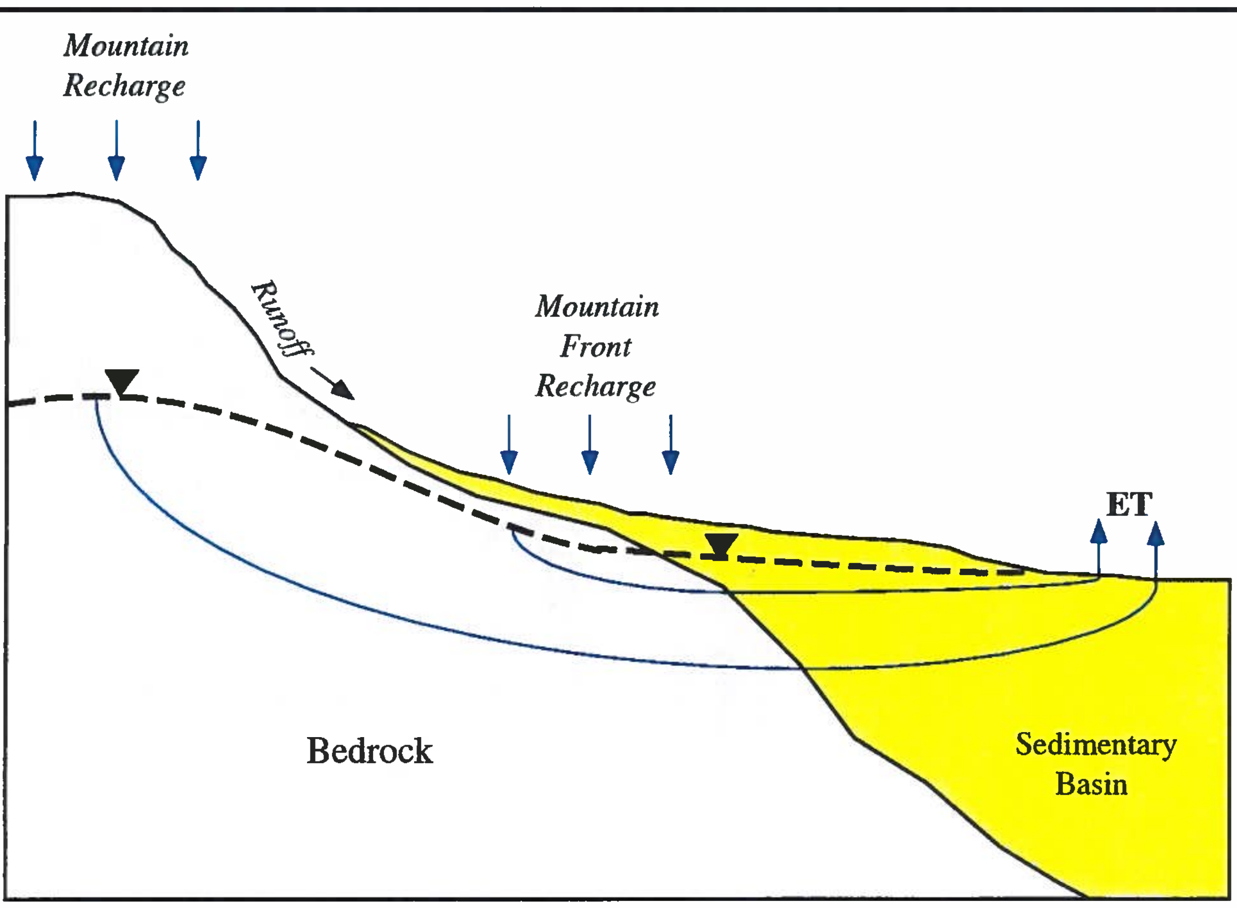


Figure 3.11. Conceptual diagram illustrating mountain front recharge.

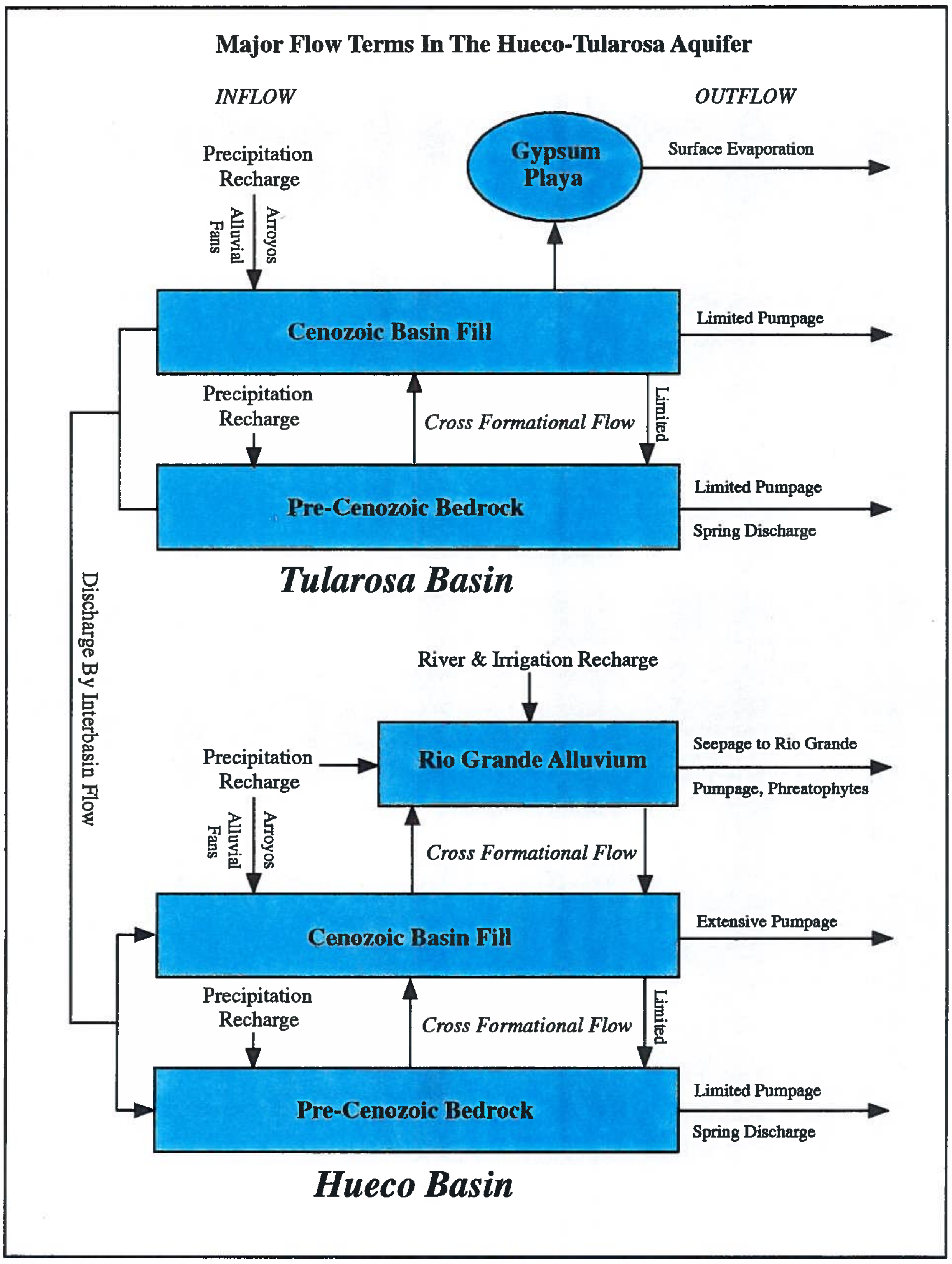


Figure 3.12. Major flow components of the Hueco - Tularosa aquifer.

amount of recharge to the Hueco Bolson. In 1993, recharge by injection averaged 3,800 acre-ft/year (USEPA, 1995). This volume is about 2% of the 188,000 acre-ft/year pumped from the aquifer in 1993 (USEPA, 1995).

Discharge Areas

Discharge from the Hueco-Tularosa aquifer under natural conditions is by direct evaporation from bare soil where the capillary fringe is near land surface (at wet playas), by leakage to springs and to streams, by consumptive use by phreatophytes, and by interbasin and cross-formational flow (Figure 3.12). Well pumpage accounts for the largest component of discharge from the aquifer.

Ground water is discharged from the Tularosa Basin by well pumping, by evaporation on the wet playas, by spring discharge, and by interbasin discharge to the Hueco Basin. Ground-water withdrawals for irrigation totaled 22,720 acre-ft in the Tularosa Basin in 1980 (USBR, 1984). Municipal pumping accounted for another 1,474 acre-ft of withdrawal (USBR, 1984). The amount of discharge by interbasin flow to the Hueco Basin is an estimated 3,700 acre-ft/year (Orr and Risser, 1992). Quantities of ground-water discharge due to leakage to springs and evaporation at playas are not known.

Most discharge in the Hueco Bolson is due to withdrawals for municipal, industrial, and military water supply. In 1994 the volumes of ground water pumped from the Hueco Bolson reportedly were 53,090 acre-ft by the City of El Paso, 108,569 acre-ft by Ciudad Juarez, and 18,000 acre-ft by military and other sources (PSB, 1997). 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 3.13). Recent trends indicate that municipal pumpage in Mexico increased about 12.5% between 1990 and 1994 (Figure 3.14). Municipal and military pumpage in the United States decreased 24.0% during the same time interval (Figure 3.14). 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.

Nearly all of the ground water in the Hueco Bolson flowed toward the Rio Grande during predevelopment times (White, 1987). There the ground water moved upward through the Rio Grande alluvium and discharged by channel seepage and by consumptive use by phreatophytes. Average simulated discharge from the Hueco Bolson to the Rio Grande between 1903 and 1920, before substantial development of the aquifer, was 6,864 acre-ft/year (Meyer, 1976).

Heavy pumpage in the Hueco Bolson reversed the hydraulic head gradient between the alluvium and the bolson aquifer in some areas. In areas where pumpage from the bolson is not great, the hydraulic head gradient between the Hueco Bolson and alluvium remains positive and artesian conditions exist. Well 49-39-202, a deep artesian well beneath the Rio Grande alluvium in the Fabens area maintained a head of 22.87 ft above land surface when it was last measured in 1978. This data clearly implies cross-formational flow from the Hueco Bolson to the Rio Grande alluvium in areas not influenced by substantial pumping.

Water Quality

General hydrochemistry

General water quality of the Hueco-Tularosa aquifer is shown in the regional stiff map (Plate 1). 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 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 Juarez area are generally less than 1,000 mg/L. The approximate thickness of the freshwater lense (TDS less than 1,000 mg/L) is shown in Figure 3.15.

Several sets of hydrochemical analyses are clustered according to distinct hydrochemical groupings (Figure 3.16). 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 Juarez municipal wells.

The mountain and mountain front samples along the Sacramento Mountains (group 1) cluster mostly as Ca-HCO_3-SO_4 and Ca-Cl-SO_4 waters, except for ground waters high in the Sacramento Mountains which are Ca-HCO_3 ground waters. Ground waters with greater than 1,000 mg/L TDS have a Ca-Cl-SO_4 signature, and ground waters with less than 1,000 mg/L TDS have a Ca-HCO_3-SO_4 signature. These ground waters are influenced by dissolution of limestone and gypsum.

The mountain and mountain front samples in group 2 are Ca-HCO_3 and mixed cation-HCO_3-SO_4 type ground waters with TDS less than 1,000 mg/L. Eastward along the basin floor, ground waters have a Na-Cl-SO_4 and mixed cation-SO_4-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-HCO_3 and Na-HCO_3-Cl type ground waters (group 3). Chloride increasingly becomes a dominant anion basinward of this mountain recharge area. Typically sampled from alluvial fans, these waters, having evolved from Ca-HCO_3 ground waters in the mountains, have probably undergone cation exchange releasing bound sodium for calcium in solution.

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 SO_4, and lower concentrations of HCO_3 than upgradient waters. These are principally Na-Cl and Na-Cl-SO_4 ground waters. TDS is usually less than 1,000 mg/L just east of the Franklin Mountains and is greater than 1,000 mg/L in most samples collected along the axis of the basin.

Group 5 samples were collected from Ciudad Juarez municipal wells. Ground waters are Ca-Na-mixed anion to Na-Cl-SO_4 type ground waters with salinities less than 1,000 TDS. Ca-Na dominated waters are located at distances from the river, and Na-dominated waters are commonly found near the Rio Grande.

Origin of solutes in the El Paso/Ciudad Juarez area

Group 4 ground waters may evolve from group 3 ground waters by a process of replacement of sodium for Ca and Mg, by the loss of HCO_3, and by the addition of Cl and SO_4. The trend shown in the piper plot may result from the geochemical evolution of ground waters from the flanking highlands along with mixing with ground waters moving south along the axis of the basin (Figure 3.17).

The most likely sources of Ca and Mg in group 3 and group 4 ground waters includes dissolution of calcite, dolomite, and gypsum:

$$CaCO_3 + H_2O + CO_2 = Ca + 2HCO_3 \qquad (3.1)$$

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O = Ca + Mg + 4HCO_3 \qquad (3.2)$$

$$CaSO_4 \bullet 2H_2O = Ca + SO_4 + 2H_2O \qquad (3.3)$$

Plotting the quantity (Ca + Mg) against HCO_3 and drawing a line with a slope of 1:2 gives the amount of calcium and magnesium derived from dissolution of calcite (1 mole Ca to 2 moles HCO_3) and dolomite (1 mole of [Ca+Mg] to 2 moles of HCO_3). Many of the

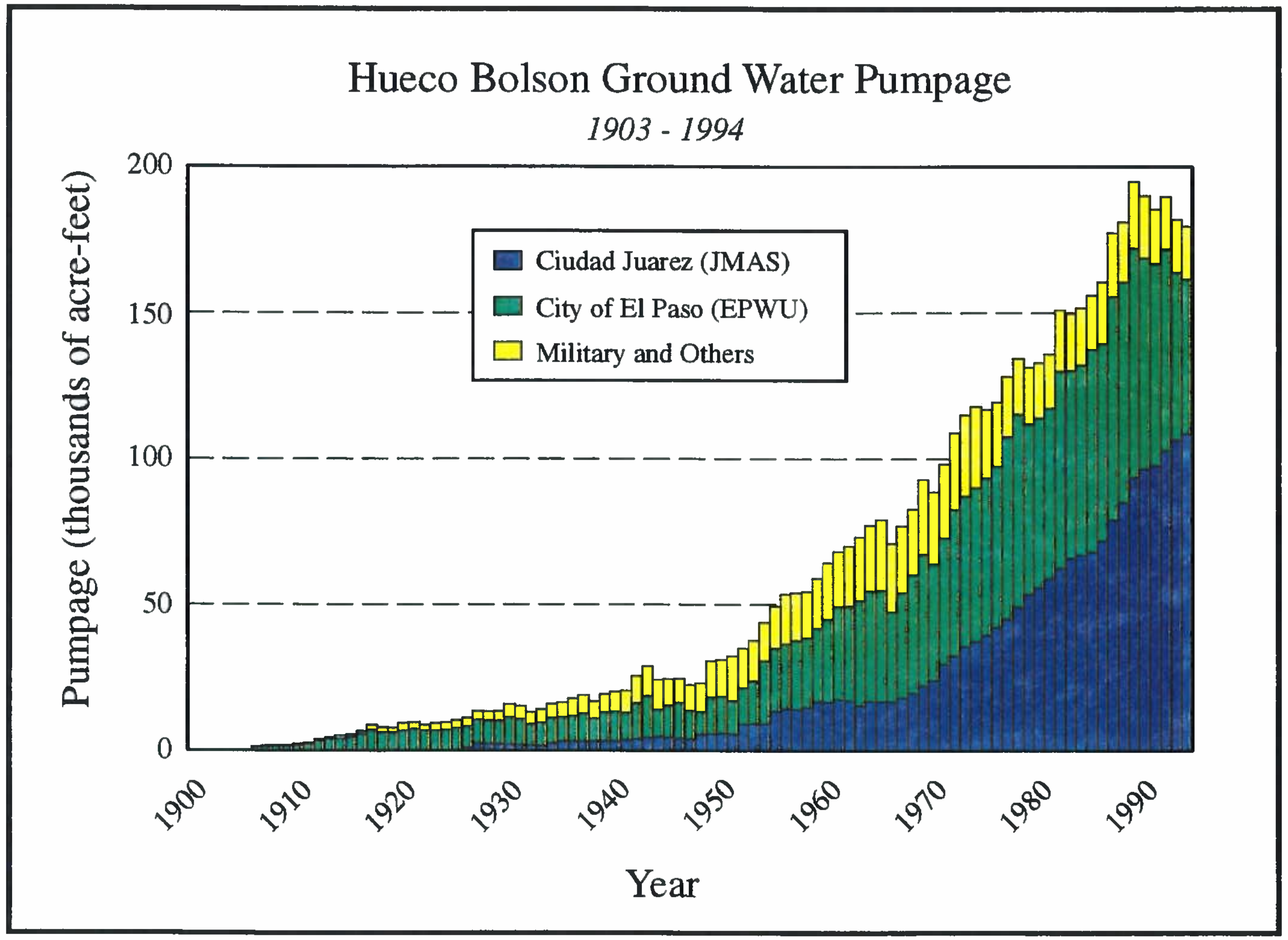
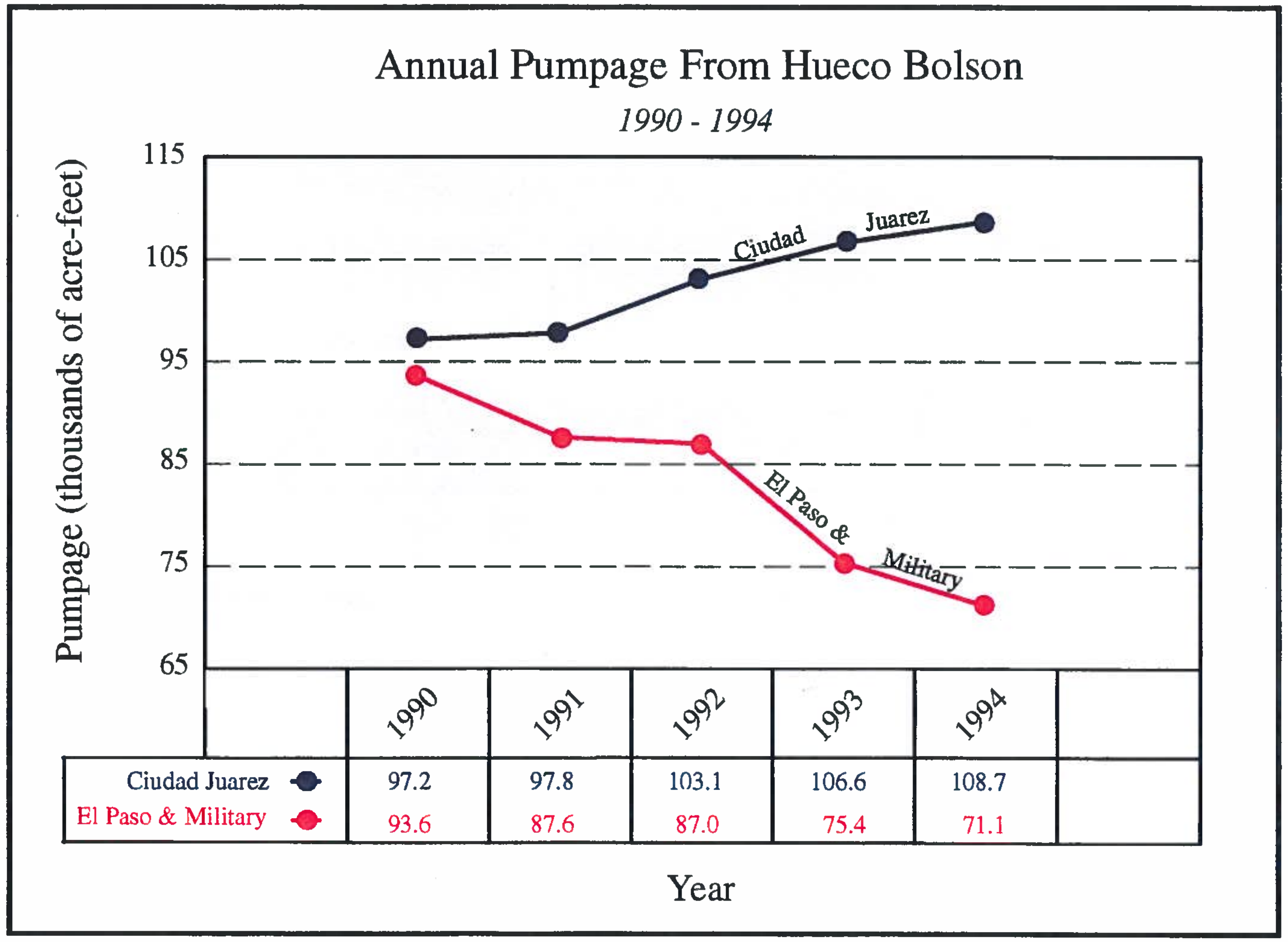


Figure 3.13. Ground-water pumpage from the Hueco Bolson; 1903 - 1994 (source of data, City of El Paso Public Services Board).



	1990	1991	1992	1993	1994
Ciudad Juarez ●	97.2	97.8	103.1	106.6	108.7
El Paso & Military ●	93.6	87.6	87.0	75.4	71.1

Figure 3.14. Ground-water pumpage from the Hueco Bolson; 1990 - 1994 (source of data, City of El Paso Public Services Board; Junta Municipal de Agua y Saneamiento).

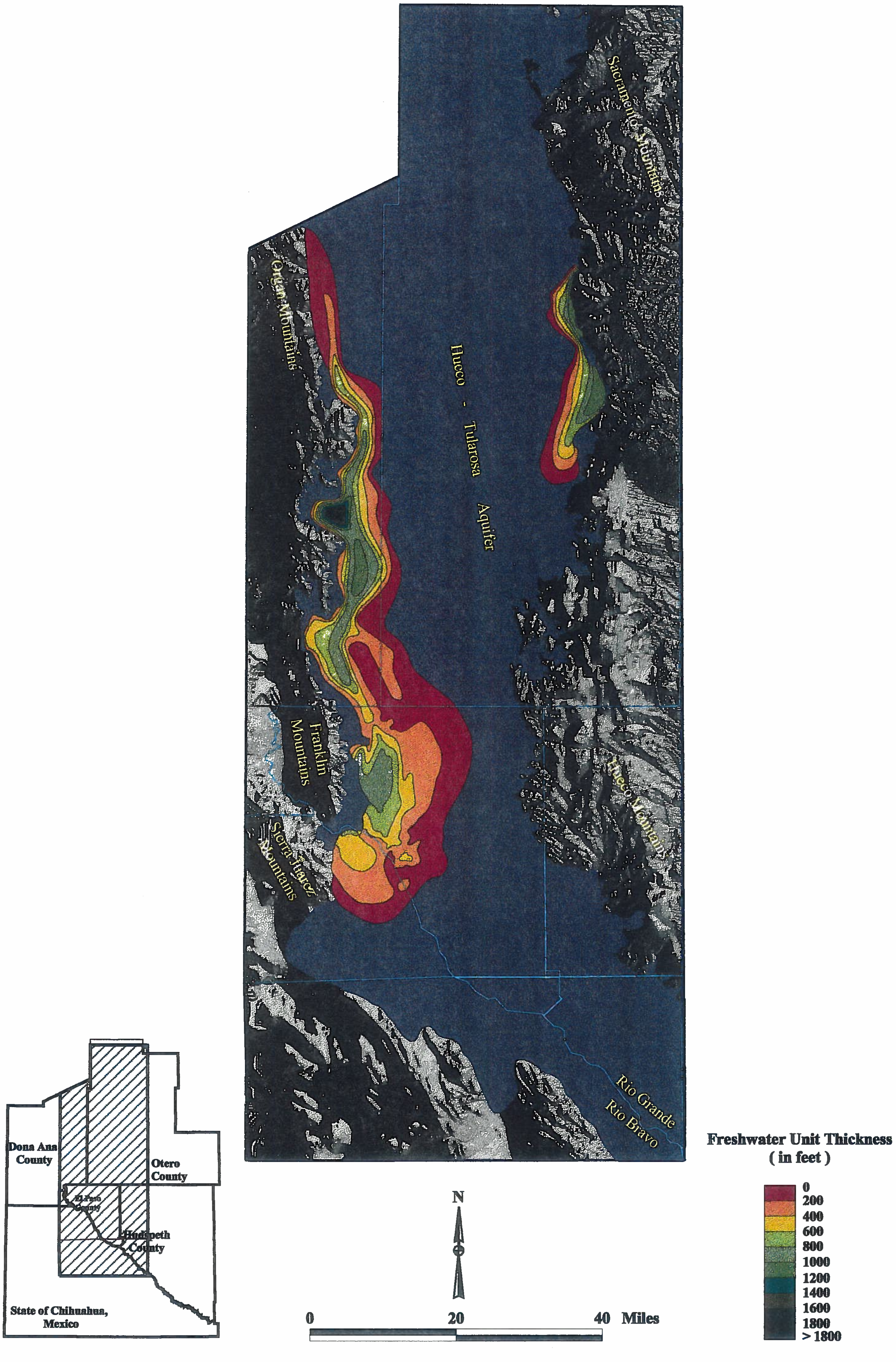


Figure 3.15. Approximate thickness of the freshwater unit (TDS < 1,000 mg/L) in the Hueco - Tularosa aquifer (modified from maps prepared by McLean, 1970, and Lee Wilson and Associates, 1986).

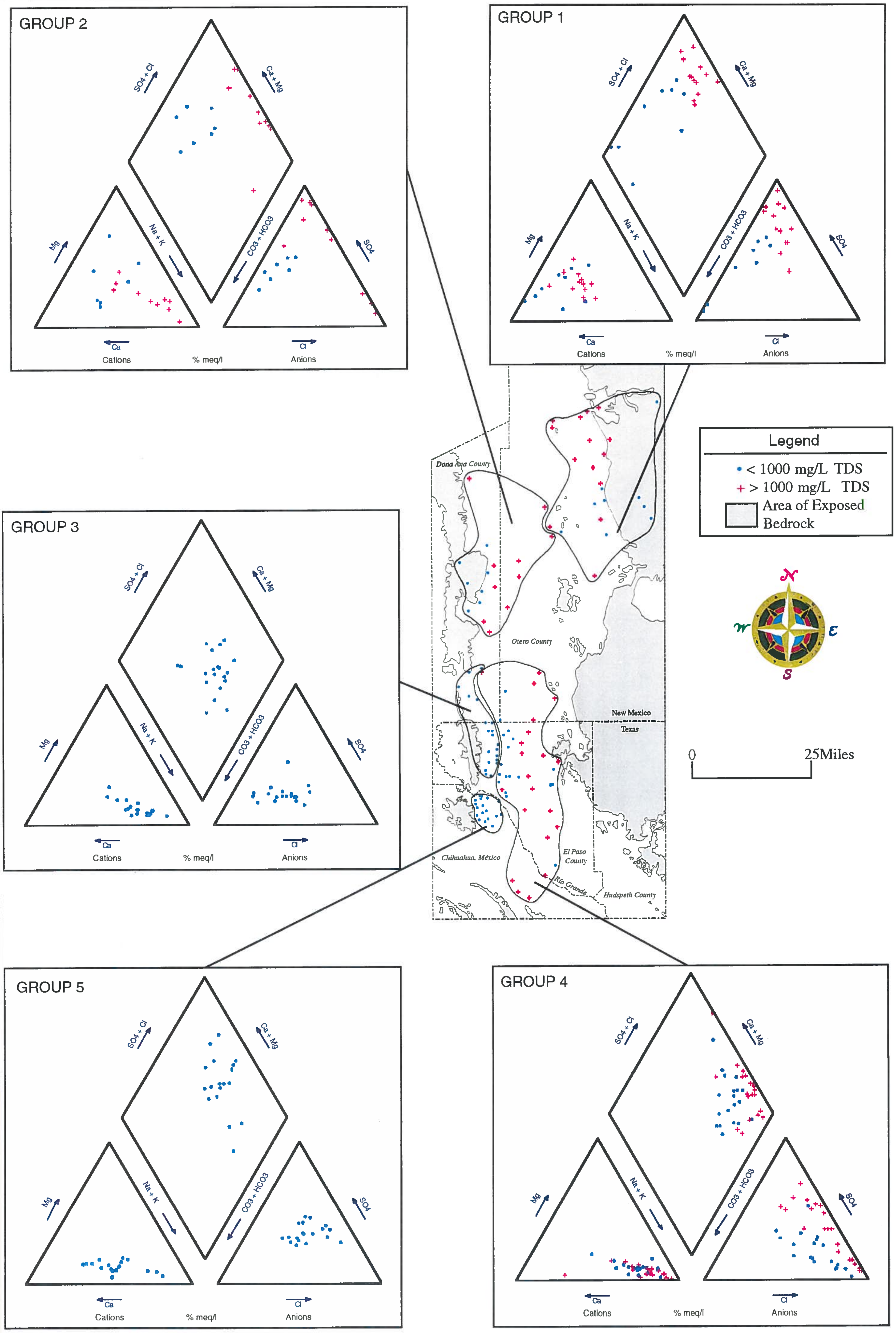


Figure 3.16. Piper diagrams illustrating geochemical types for the Hueco-Tularosa aquifer (source of data, Comision Nacional Del Agua; Junta Municipal de Agua y Saneamiento; Instituto Nacional de Estadistica, Geografia e Informatica; Texas Water Development Board).

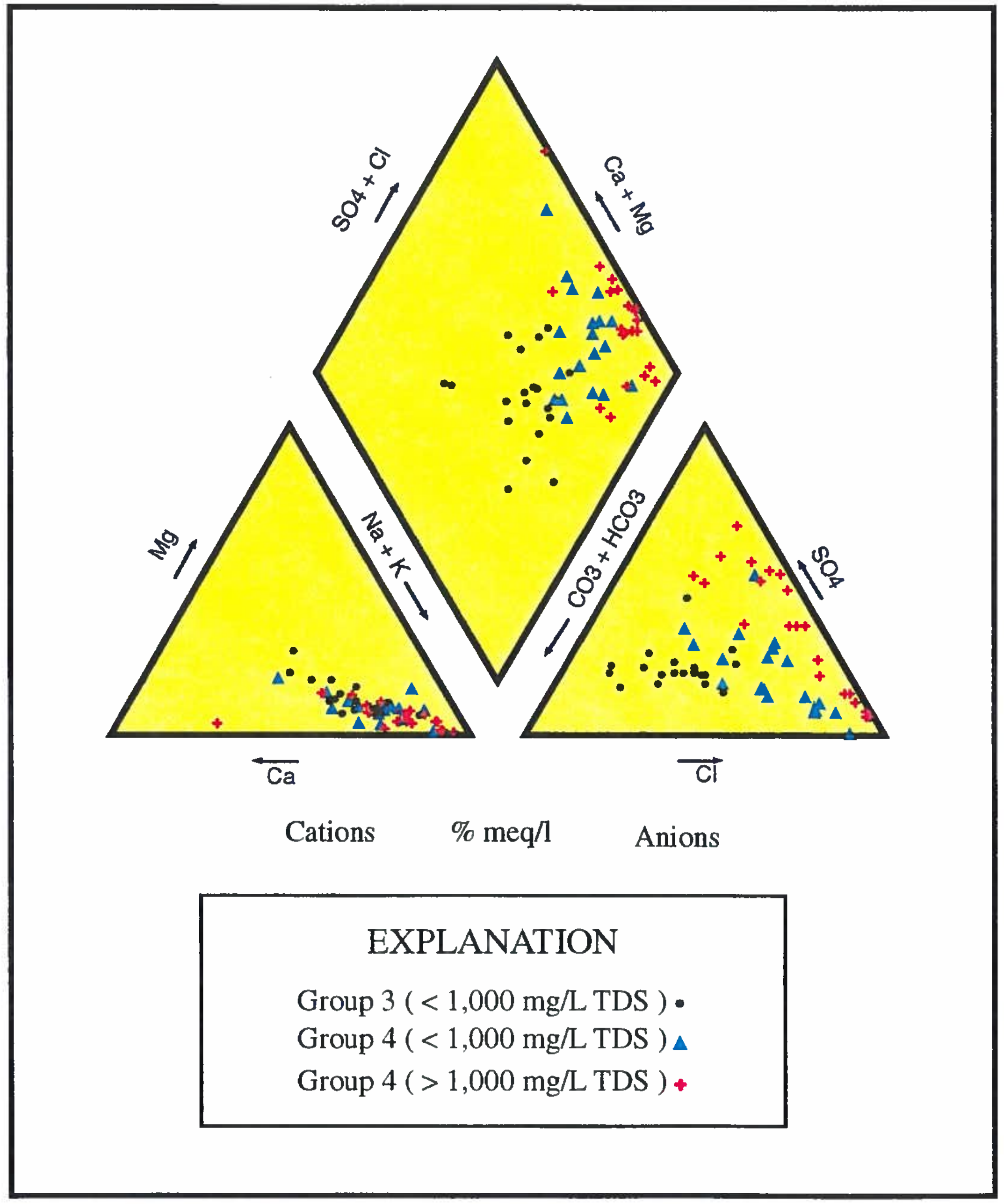


Figure 3.17a. Piper diagram for group 3 and group 4 ground waters in the Hueco-Tularosa aquifer (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

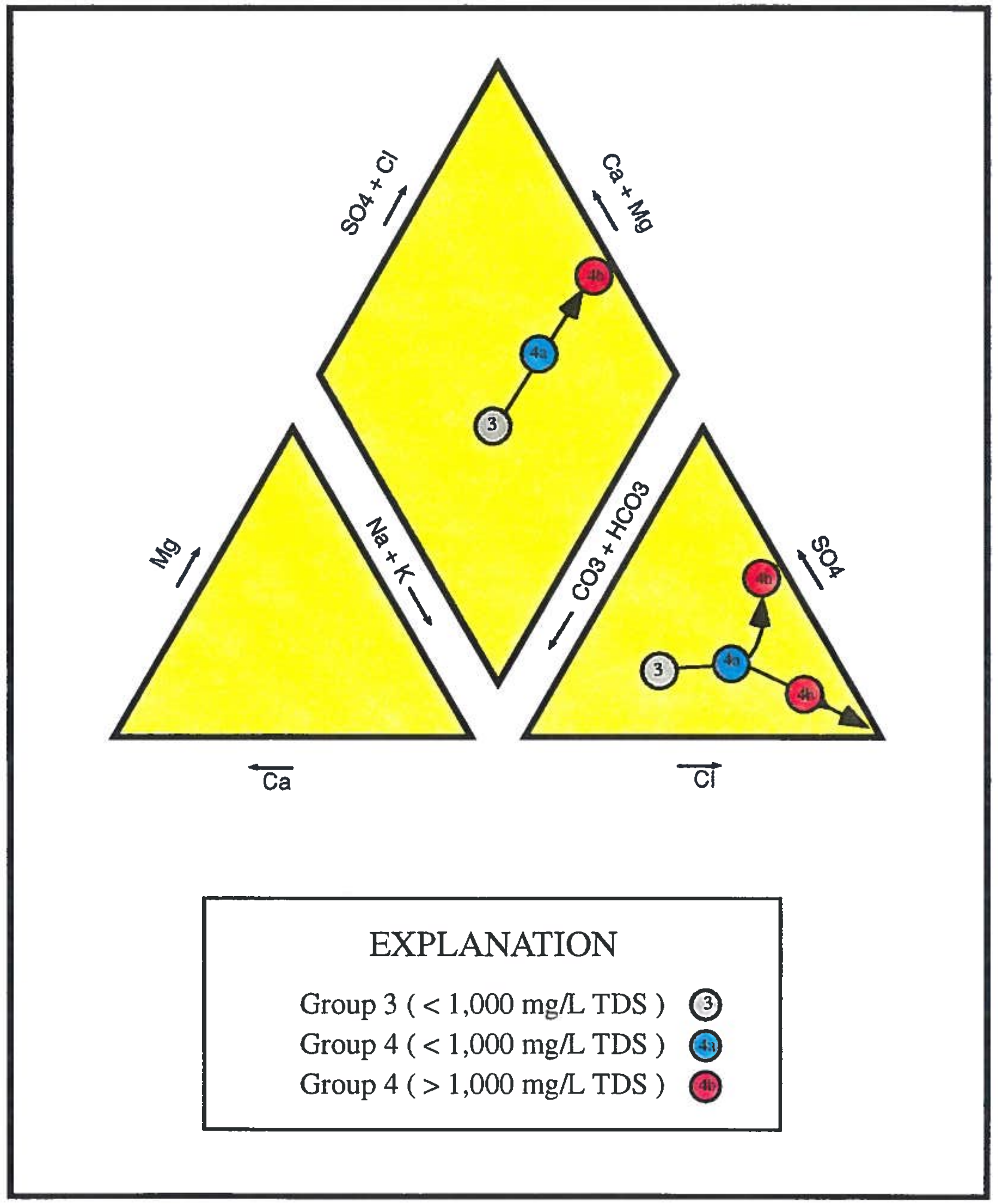


Figure 3.17b. Geochemical evolution diagram that represents possible evolutionary paths for data shown in Figure 3.17a (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

points plot near the 1:2 line (Figure 3.18), but many of the points plot above the line, indicating an additional source of Ca and Mg. To account for remaining Ca due to dissolution of gypsum, the quantity ($Ca + Mg - SO_4$) is plotted against HCO_3 (Figure 3.19). The majority of the points plot well below the 1:2 line, indicating that another process is removing Ca and Mg from solution. The few points plotting above the 1:2 line indicate an excess of Ca and Mg.

Cation exchange is a process that removes Ca and Mg from ground waters by substitution for bound Na on clays:

$$Na_2\text{-clay} + Ca^{+2} = Ca\text{-clay} + 2Na^{+} \qquad (3.4)$$

$$Na_2\text{-clay} + Mg^{+2} = Mg\text{-clay} + 2Na^{+} \qquad (3.5)$$

The forward reaction may account for deficient Ca and Mg shown in Figure 3.19. Reversal of the exchange process may be the source of excess Ca and Mg in the samples that plot above the 1:2 line (Figure 3.19). To test the influence of cation exchange on the hydrochemical signature of ground waters in the study area, the molar quantities (Na - Cl) are plotted against ($Ca + Mg - SO_4 - 0.5HCO_3$). The quantity (Na - Cl) represents excess Na coming from sources other than halite dissolution (Figure 3.20). The quantity ($Ca + Mg - SO_4 - 0.5HCO_3$) represents the Ca and Mg derived from sources other than dissolution of gypsum, calcite, or dolomite. Together, these quantities represent the amount of monovalent and divalent cations available for cation exchange. A 2:1 exchange line shows how much Na is contributed from cation exchange (positive Na - Cl values) and how much Ca and Mg is contributed from the reversible exchange process (negative Na - Cl values). Nearly all of the points fit the 2:1 exchange line exceptionally well (Figure 3.20). These values reflect excess or deficient Na caused by the reversible cation exchange process.

A plot of molar (Na /Cl) vs Cl for dilute (<1,000 mg/L TDS) and slightly to moderately saline (>1,000 mg/L) water in groups 3 and 4 indicates that the (Na/Cl) ratio ranges from about 3.3 to 0.5 and decreases with increasing chlorinity (Figure 3.21). At salinities less than 8 mmols/L Cl, excess Na is due to exchange of calcium and magnesium for bound sodium on clay particles. At salinities greater than about 8 mmols/L Cl and especially above 20 mmols/L Cl, the influence of halite dissolution on the hydrochemical composition of ground water is apparent, as the sample points trend to a ratio of about 1.0.

Results indicate cation exchange and dissolution of calcite, halite, and gypsum as the principal factors influencing hydrochemical signatures in group 3 and group 4 ground waters. The contribution of mineral dissolution on hydrochemical signatures can be determined by summing the equivalent quantities of cations derived by mineral dissolution and cation exchange (Ca + Mg + Na). For example, a plot of milliequivalent ($Ca + Mg + Na - SO_4 - HCO_3$) versus (Cl) removes sources of cations due to dissolution of calcite, gypsum, and cation exchange (Figure 3.22a). The plot provides an excellent 1:1 fit. This is expected for halite dissolution; the source of residual Na and Cl that has not been removed from the milliequivalent quantities by subtraction. Removing ($-HCO_3$) from the quantity ($Ca + Mg + Na - SO_4 - HCO_3$) gives the amount of mass derived from the dissolution of calcite. As observed from the upward shift (Figure 3.22b), the amount of Ca and HCO_3 derived from dissolution of calcite is important in dilute waters only (salinities less than 10 meq/L Cl).

Removing ($-SO_4$) from the quantity ($Ca + Mg + Na - SO_4 - HCO_3$) gives the amount of mass derived from the dissolution of gypsum (Figures 3.23a & 3.23b). The plot indicates that gypsum dissolution is important in slightly saline ground waters with chlorinities greater than 4 meq/L.

The amount of halite dissolution is determined by plotting the milliequivalent quantities ($Ca + Mg + Na - Cl - HCO_3$) against the independent variable anion (SO_4). Removing (-Cl) from the quantity ($Ca + Mg + Na - Cl - HCO_3$) gives the amount of mass derived from halite dissolution (Figures 3.24a & 3.24b). The upward shift is significant in all but the most dilute ground waters. This indicates that dissolution of halite is an important process for virtually the full range of salinities in group 3 and group 4 samples.

These analyses indicate that the origin and evolution of type 3 and type 4 waters are due to the following reactions and exchange processes:

- Dissolution of calcite and dolomite in dilute ground waters.
- Dissolution of gypsum in slightly saline ground waters.
- Dissolution of halite in all except very dilute ground-waters.
- Cation exchange, favoring exchange of Ca and Mg for bound Na; some reversible exchange (Na for bound Ca and Mg) in a few ground waters.

Dissolution of specific minerals is a function of their spatial variability at locations in the basin. Halite is present in small quantities along mountain flanks and along the basin floor and probably was derived by evaporation of large amounts of very dilute, salt bearing precipitation over geologic time. Gypsum is present along the basin floor and may have precipitated in gypsum playas that formed when the Hueco Bolson was a closed drainage basin. Carbonates are present in the mountains and precipitate as caliche along mountain fronts. Other rocks, such as volcanic and intrusive igneous rocks appear to contribute little to the overall dissolved load of group 3 and group 4 ground waters.

Vertical layering of hydrochemical types in El Paso County

A series of stiff plots derived from samples collected at discrete vertical intervals during test hole drilling and water quality sampling by the U.S. Geological Survey and Texas Water Development Board allows approximation of layering of hydrochemical facies in El Paso County (Figure 3.25). Stiff clusters include samples collected between 1956 and 1967, and samples collected between 1976 and 1992. Samples collected between 1956 and 1967 may approximate predevelopment conditions, and samples collected after 1976 in heavily developed areas may reflect possible influences of mixing in vertical intervals caused by pumping from adjacent wells.

In northwestern El Paso County, hydrochemical facies include a $Ca\text{-}HCO_3$ to $Na\text{-}HCO_3$ layer that extends to 1,118 ft beneath land surface at 49-05-801 (Figure 3.25). Ground water is less than 1,000 TDS in this interval. This layer appears at 520 - 545 ft at 49-05-906 and is gradually replaced by a still-dilute, Na-Cl layer below 881 ft. The Na-Cl layer at 49-05-801 has TDS greater than 1,000 mg/L below 1317 ft. The Na-Cl facies is the only type of ground water that appears at test holes 49-05-503 and 49-05-208, increasing from dilute concentrations less than 1,000 mg/L TDS at shallow depths to concentrations that exceed 3,000 mg/L TDS at 800 ft in 49-05-208.

Test holes 49-05-634 and 49-05-906 are closely spaced and have the same general facies transitions with depth; from a $Na\text{-}HCO_3$ to $Na\text{-}HCO_3\text{-}Cl$ layer in the first sampled interval to a Na-Cl layer below 1065 and 1095 ft. Ground water in these test holes is below 1,000 mg/L TDS. Little perceptible change of hydrochemical facies between test holes 49-05-634 and 49-05-906 may indicate that hydrochemical facies have not changed much with time in this area. Well samples were collected in 1966 at 49-05-906 and in 1992 at 49-05-634.

East of test hole 49-05-906, ground waters are Na-Cl to $Na\text{-}Cl\text{-}SO_4$ types in all sampled intervals with TDS usually less than 1,000 mg/L, increasing to more than 1,000 mg/L at 49-06-603 and 49-06-901. These test holes were sampled in 1986 and are located along the axis of the bolson, at distances from regions of extensive aquifer development and drawdown. Since drawdowns are small, samples at 49-06-603 and 49-06-901

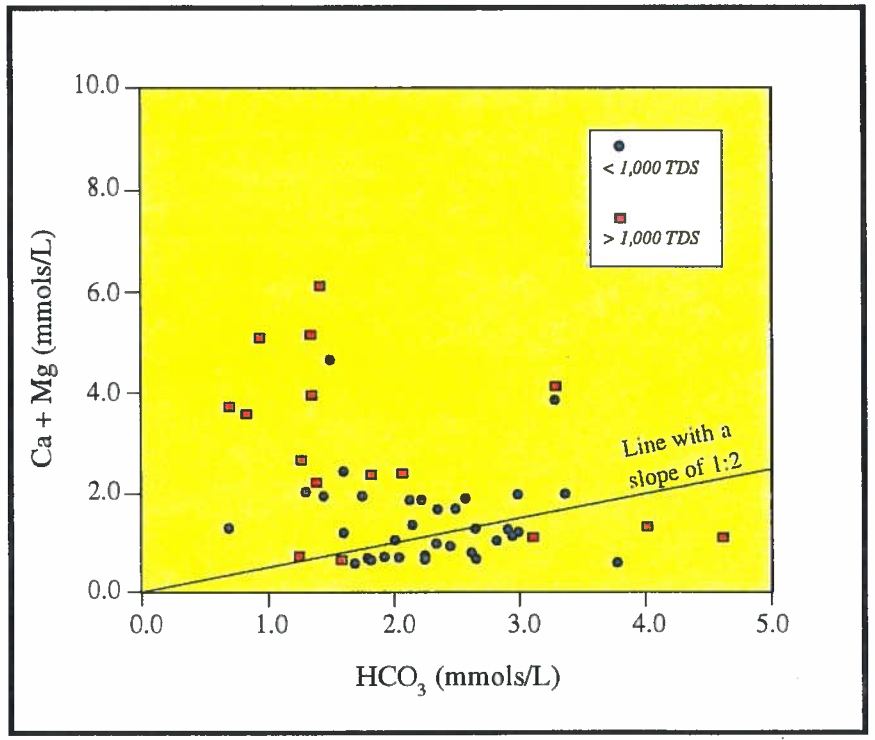


Figure 3.18. (Ca + Mg) vs HCO$_3$ plot, group 3 and group 4 ground waters (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

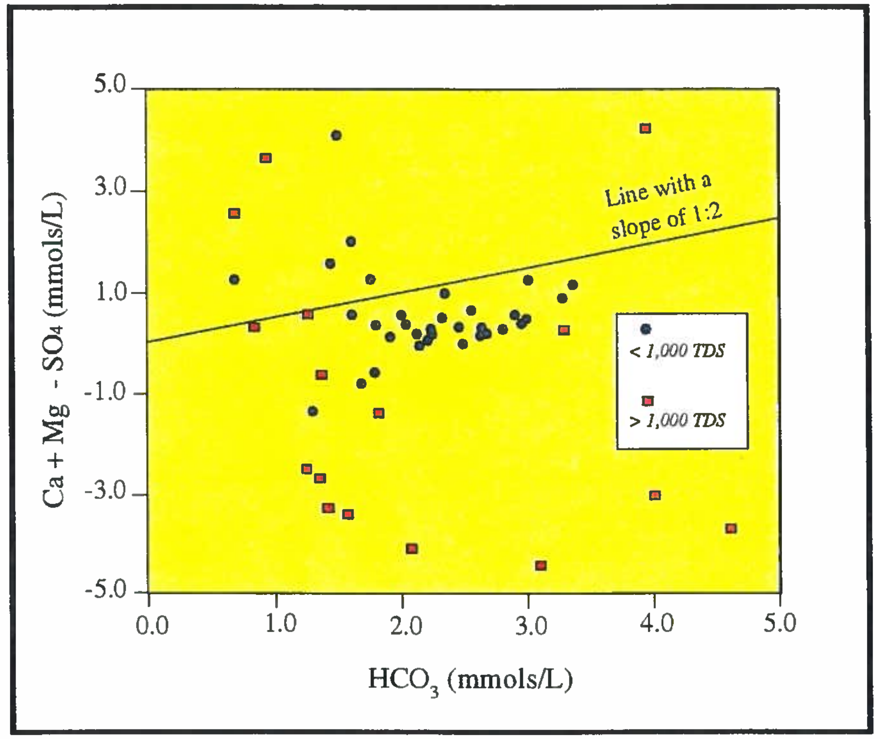


Figure 3.19. (Ca + Mg - SO$_4$) vs HCO$_3$ plot, group 3 and group 4 ground waters (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

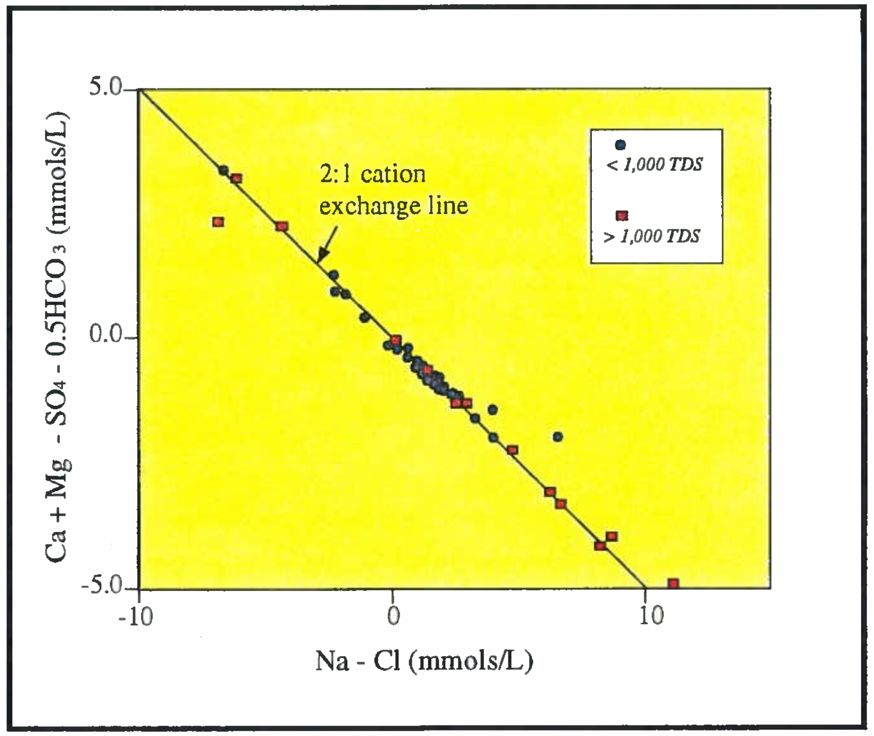


Figure 3.20. (Ca + Mg - SO$_4$ - 0.5HCO$_3$) vs (Na - Cl) plot, group 3 and group 4 ground waters (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

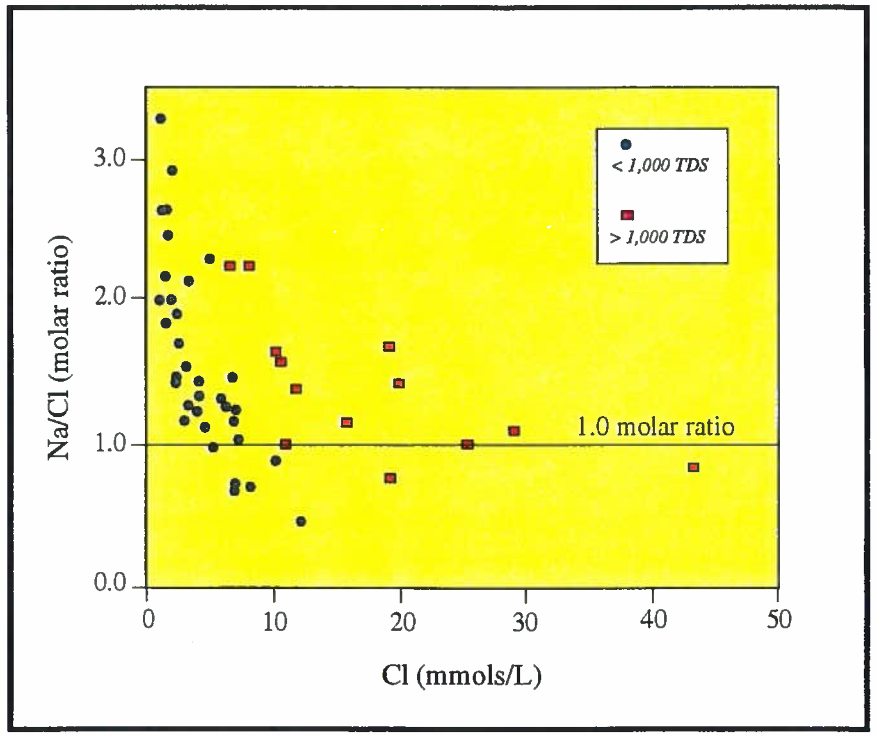


Figure 3.21. (Na/Cl) vs Cl plot, group 3 and group 4 ground waters (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

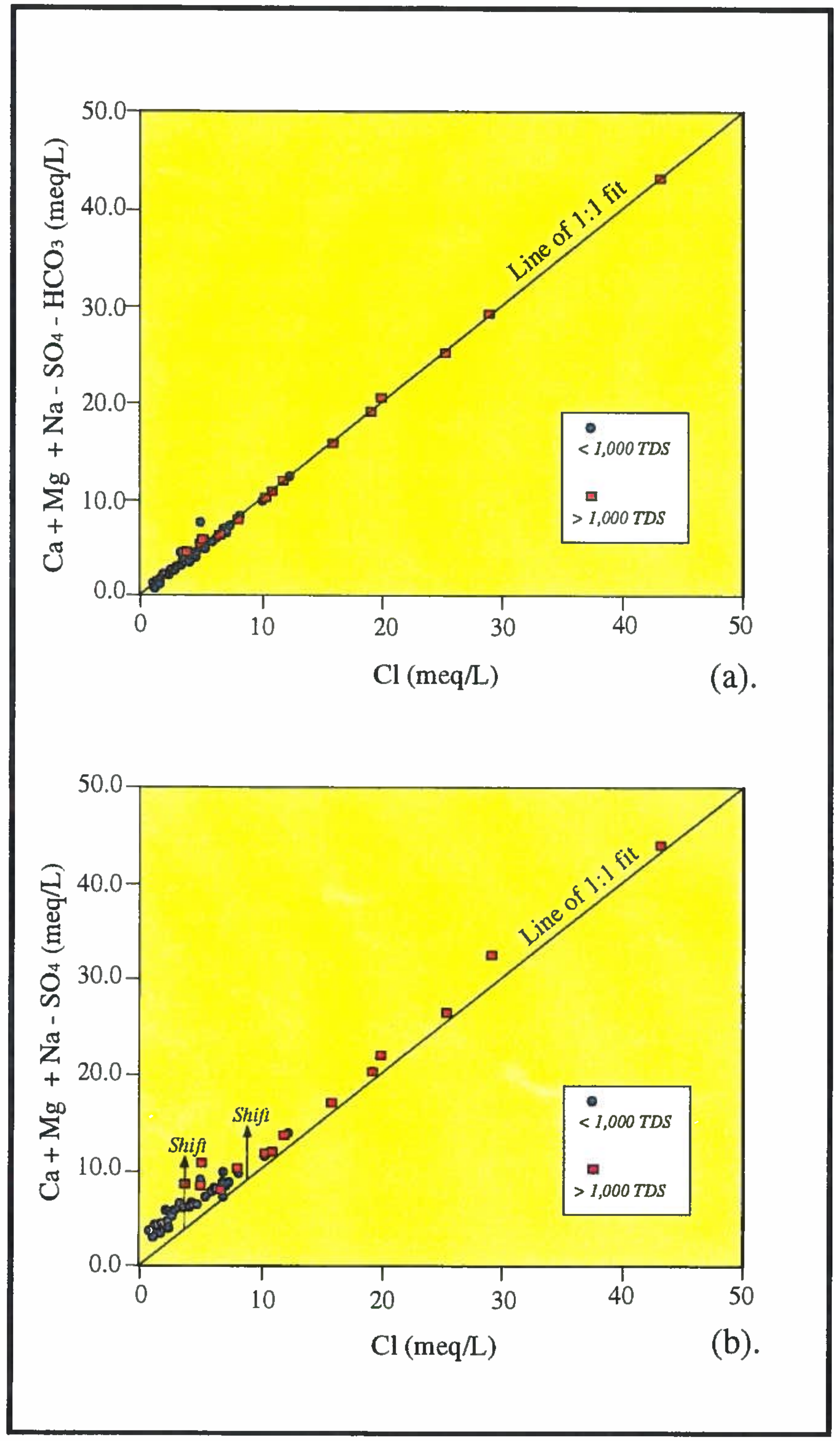


Figure 3.22. Upper figure (a); a plot of (Ca + Mg + Na - SO$_4$ - HCO$_3$) vs Cl in group 3 and group 4 ground waters gives an excellent 1:1 fit. Lower figure (b); the shift caused by removing (-HCO$_3$) from the term (Ca + Mg + Na - SO$_4$ - HCO$_3$) gives the amount of mass due to dissolution of calcite (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

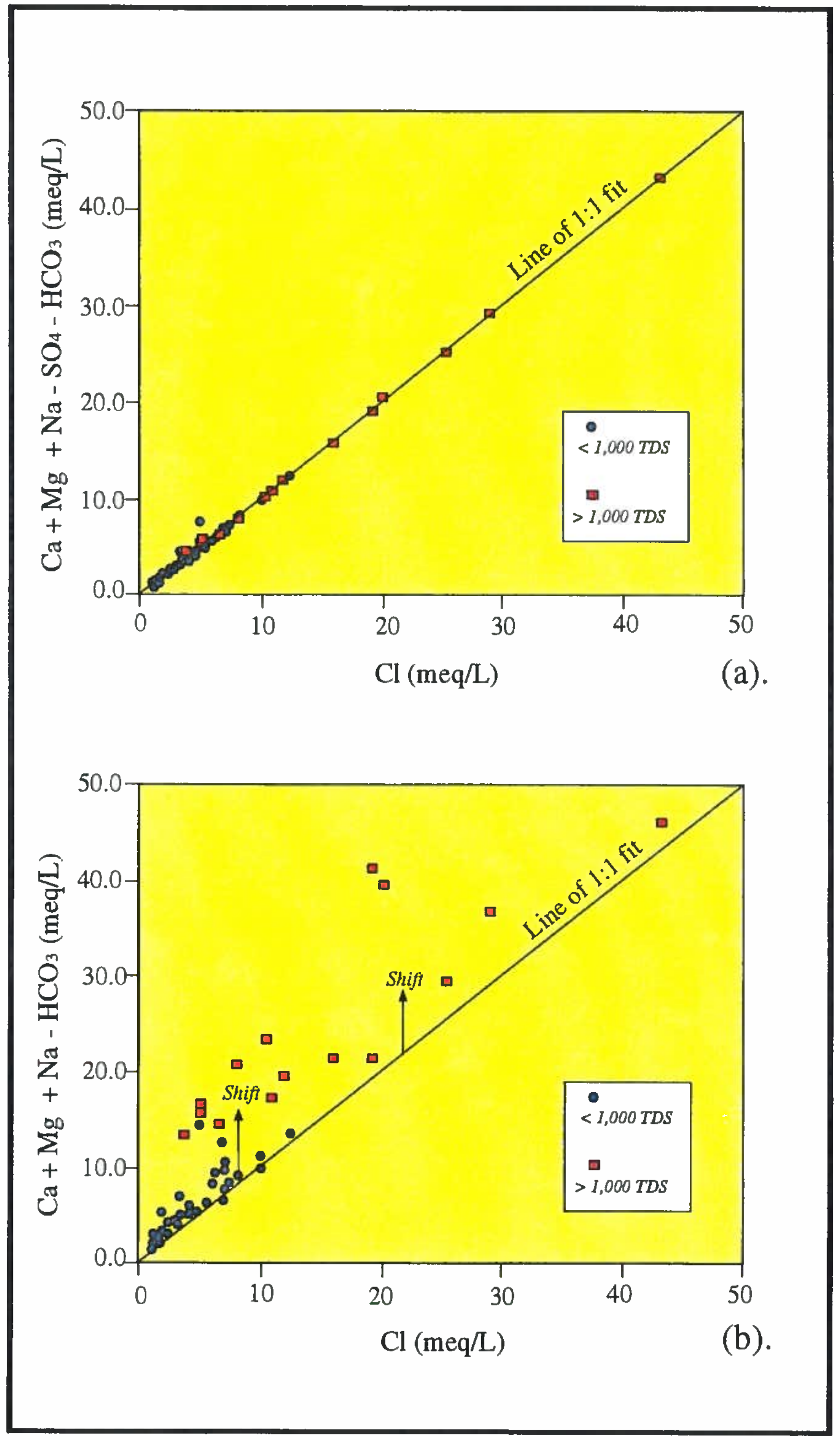


Figure 3.23. Upper figure (a); a plot of (Ca + Mg + Na - SO$_4$ - HCO$_3$) vs Cl in group 3 and group 4 ground waters gives an excellent 1:1 fit. Lower figure (b); the shift caused by removing (-SO$_4$) from the term (Ca + Mg + Na - SO$_4$ - HCO$_3$) gives the amount of mass due to dissolution of gypsum (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

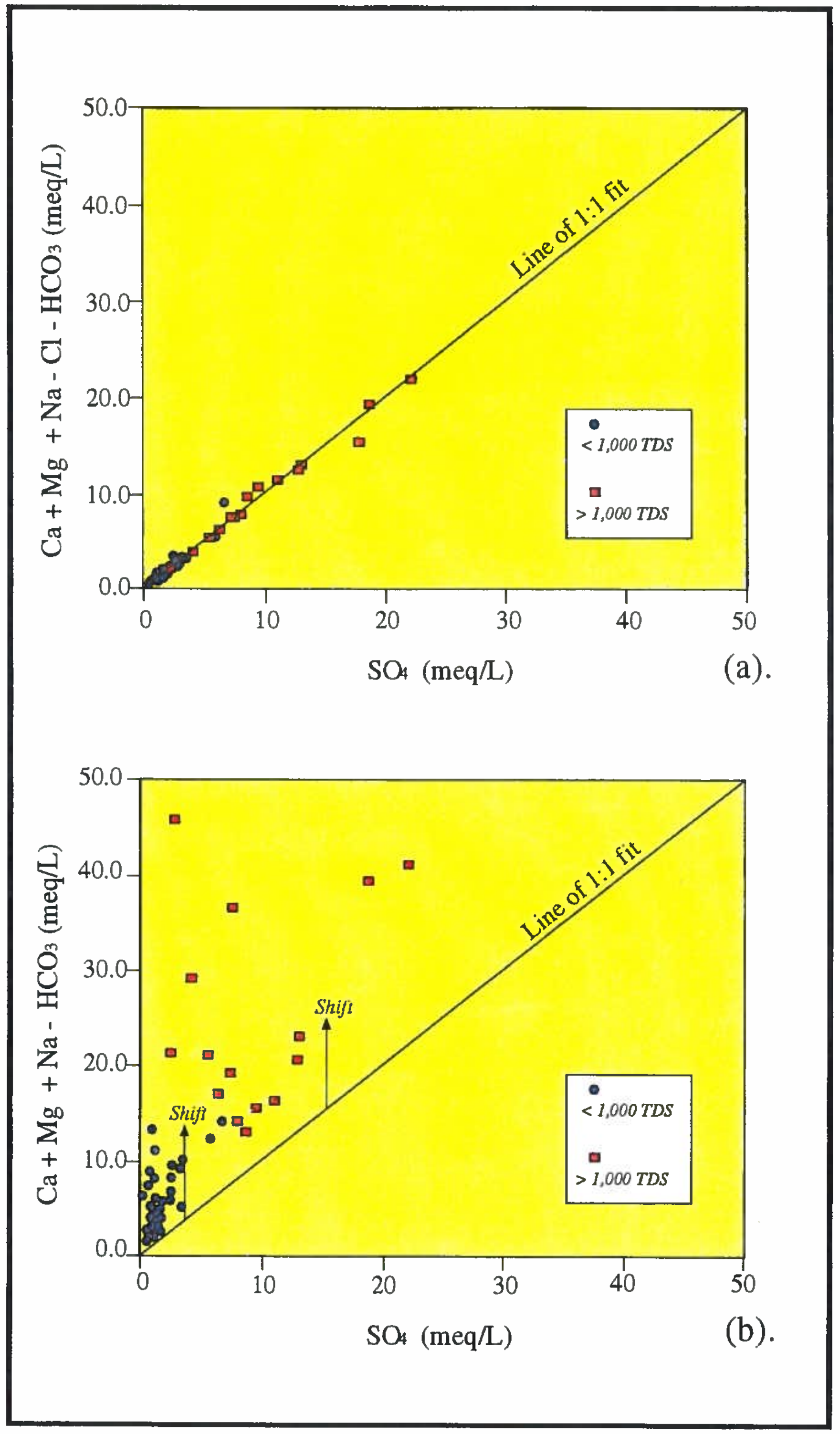


Figure 3.24. Upper figure (a); a plot of (Ca + Mg + Na - Cl - HCO$_3$) vs SO$_4$ in group 3 and group 4 ground waters gives an excellent 1:1 fit. Lower figure (b); the shift caused by removing (-Cl) from the term (Ca + Mg + Na - Cl - HCO$_3$) gives the amount of mass due to dissolution of halite (source of data, Texas Water Development Board; Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

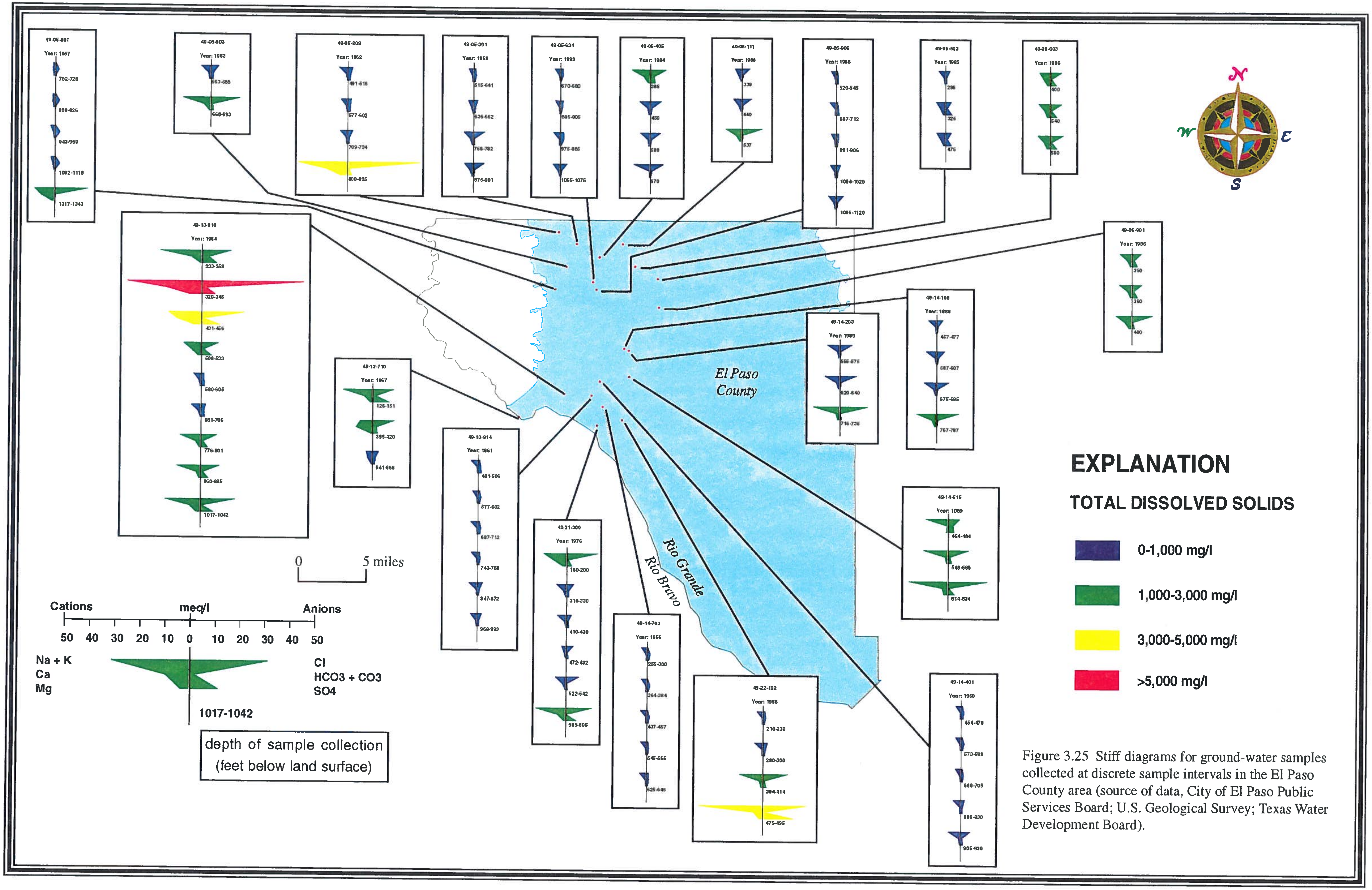


Figure 3.25 Stiff diagrams for ground-water samples collected at discrete sample intervals in the El Paso County area (source of data, City of El Paso Public Services Board; U.S. Geological Survey; Texas Water Development Board).

may almost reflect predevelopment conditions, despite the fact that they were sampled fairly recently. Results indicate that the Na-Cl layer thickens to the east, and grades laterally into a Na-Cl-SO_4 type ground water.

In southern El Paso County, the dilute, Na-HCO_3 layer is present in test holes 49-13-914, 49- 14-703, 49-14-401, and 49-22-102. The Na-Cl layer is first seen at 847 ft in well 49-13-914, at 805 ft in well 49-14-401, and at 280 ft at 49-22-102 (Figure 3.25). The Na-HCO_3 layer thickens to the east (Roger Sperka, written communication, 1990). In well 49-22-102, the Na-Cl water is first seen at 280 ft and is less than 1,000 mg/L TDS, increasing to greater than 1,000 TDS between 394 and 414 ft, and grading into a Na-Cl-SO_4 water with TDS greater than 3,000 mg/L at 475 ft. The Na-HCO_3 layer is a dilute ground water that is overlain by slightly to moderately saline, or brackish ground water in the Rio Grande alluvium. Shown at 180 ft in 42-21-309 and at 126 ft at 49-13-710, the brackish layer is a Na-Cl to Na-Cl-SO_4 ground water that forms by evaporation, dissolution of halite, and dissolution of gypsum in the alluvium (see Rio Grande aquifer; Chapter 5).

An anomaly is shown at test hole 49-13-810, where the Na-Cl-SO_4 type ground water is present at several intervals between 223 and 533 ft. The only dilute samples in this test hole are Na-HCO_3-SO_4 ground waters and Na-Cl-SO_4 ground waters at 580 and 681 ft. Na-Cl-SO_4 ground waters with TDS greater than 1,000 mg/L are sampled at test intervals between 776 and 1042 ft in the well.

Historical change

The thin freshwater zone is underlain and in some places overlain by inferior quality ground waters. Mixing due to pumpage, leakage from mud interbeds and artesian confining beds, cascading waters along well casings and screens, lateral salt water encroachment, and potential upconing have started to degrade the freshwater zone. The volume of the freshwater lense is decreasing as it is depleted due to heavy pumping. Chloride has increased over time in many of the municipal wells in El Paso and Ciudad Juarez (Figure 3.26). Chloride now exceeds the maximum recommended limit in several of the wells in the area (Figure 3.26).

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 3.27). Samples derived from 49-05-503 indicate that the well has experienced increasing chlorinity and little change in the concentration of other ions (Figure 3.27). The well screen is 361 to 571 ft 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 285 and 751 ft 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 3.27). This well is located near the Rio Grande and is screened between 344 and 531 ft. JMAS-15, a Ciudad Juarez 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 (Figure 3.27).

Salinization depends to one degree or another on several factors, including thickness of freshwater saturated sediments, location and pumping rate of the well, depth of the well screen, well construction, hydrochemistry of the basin fill, distribution and continuity of mud interbeds, and density of saline water (Orr and Risser, 1992). There are several reasons possible why salinity increased in wells. Upconing of saline ground water (Figure 3.28a) has been suggested as a possible cause of salinization (Orr and Risser, 1992). Theoretical studies have used variable density models to evaluate the potential for saline encroachment due to upconing (Orr and Risser, 1992; Groschen, 1994). Results of modeling studies seem to be conflicting. The study by Groschen (1994) concluded that horizontal to vertical anisotropy in the basin could preclude upconing (Figure 3.28b). The study by Orr and Risser (1992) did not necessarily draw the same conclusion. Conflicting results might be resolved with a well-posed field study.

Lateral migration may account for salinization of some wells (Figure 3.28c). Hydrochemical mapping indicates that ground water is more saline along the axis of the Hueco Bolson. Pumpage may induce inferior quality water to move to wells where drawdown cones have reversed the natural hydraulic head gradient. In heavily developed areas, leakage of inferior quality ground water from mud interbeds may contribute to higher salinity of wells (Figure 3.28d). Wells often have multi-level screens in the more-permeable layers, and the leakage that arises from the intervening semipervious confining beds can create poorer quality yields from wells (White, 1987).

Downward movement of saline ground-water from the brackish zone near the Rio Grande probably accounts for some of the degradation of deeper wells close to the river (Figure 3.28e). It is physically more realistic for a denser, salt-laden water to move vertically downward through layered basin fill than for the dense ground water to move vertically upward against the forces of gravity. A well that is not well-constructed or that is old and corroded may act as a conduit for vertical migration of saline ground water into the freshwater zone due to differential pressures in the pumped layer and overlying layer that is not pumped (Figure 3.28f).

As the freshwater bearing zone becomes thinner by depletion in heavily developed areas, especially where the wells are overlain by the brackish, Na-Cl and Na-SO_4-Cl layer, drawdowns will result in the juxtaposition of saline water at well screens as the freshwater is pumped out from beneath it (Figures 3.28g and 3.28h).

The cause of salt water encroachment is complex and several of these processes may combine to exert a substantial influence on water quality in wells. More work on this phenomena, possibly using environmental isotopes, will be needed to assess mechanisms of salinization.

Contaminant Susceptibility and Evidence of Contamination

The Hueco-Tularosa aquifer is moderately susceptible to contamination. The Texas portion of the aquifer has a moderate ground-water pollution potential (DRASTIC index) that ranges mostly from 80 -109 for general, municipal, and industrial sources (Cross and Terry, 1991). The DRASTIC index is 110 - 124 along the slopes of the El Paso Valley, where older bolson material has been incised by the Rio Grande.

Aside from contamination by encroachment of naturally occurring, poorer quality ground water, there are anthropogenic sources of contamination along the El Paso/Ciudad Juarez corridor. Potential sources of contamination within El Paso wellhead protection areas (WHPA) include (Cross and Terry, 1991): abandoned wells (19 identified in the WHPA); active water wells, some of which may be old or poorly constructed (747); underground storage tanks (73); municipal sewage lines (5 major lines 20 inches or larger); septic tanks (812); dumps (several); underground pipelines (13 natural gas pipelines and 2 fuel oil pipelines); treated sewage injection wells (several identified near the northern-most WHPA); abandoned animal feedlots (several identified from pre-1958 aerial photographs).

Point source contamination has been detected in ground water at several sites in the El Paso area. Point source contaminants include toxic trace elements (arsenic, copper, lead, zinc), PCB's, benzene, volatile organics, glycols, gasoline, diesel, jet fuel, unspecified chemicals, and waste oil (Texas Groundwater Protection Committee, 1992). Screenings for contaminants in the water distribution system of El Paso occasionally have detected low-levels of petroleum hydrocarbons and volatile organic contaminants. The sources of these contaminants are unverified (Robert

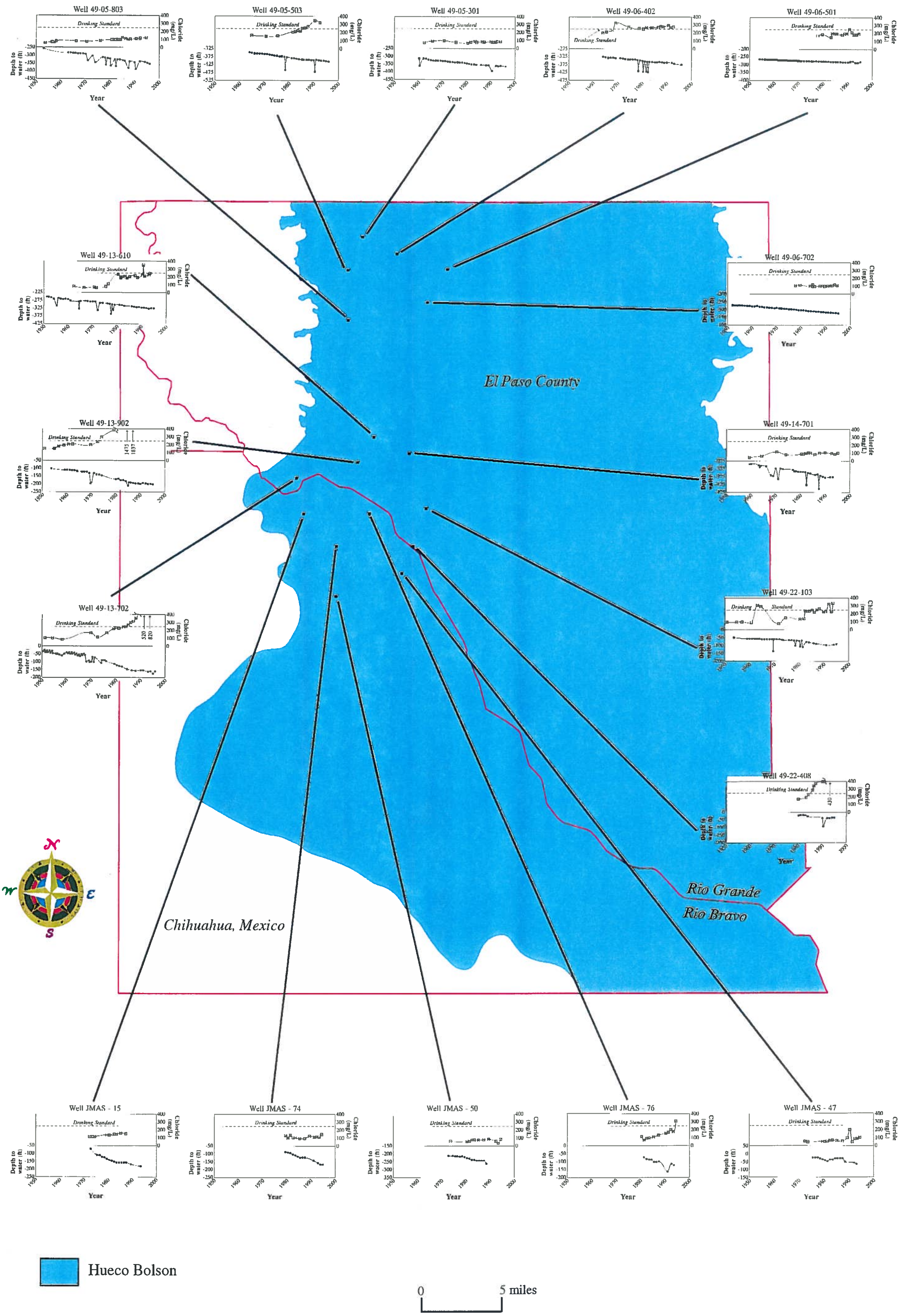


Figure 3.26. Comparison of change of chloride in ground water with drawdown in City of El Paso and Ciudad Juarez municipal water wells (source of data, Texas Water Development Board; Junta Municipal de Agua y Saneamiento).

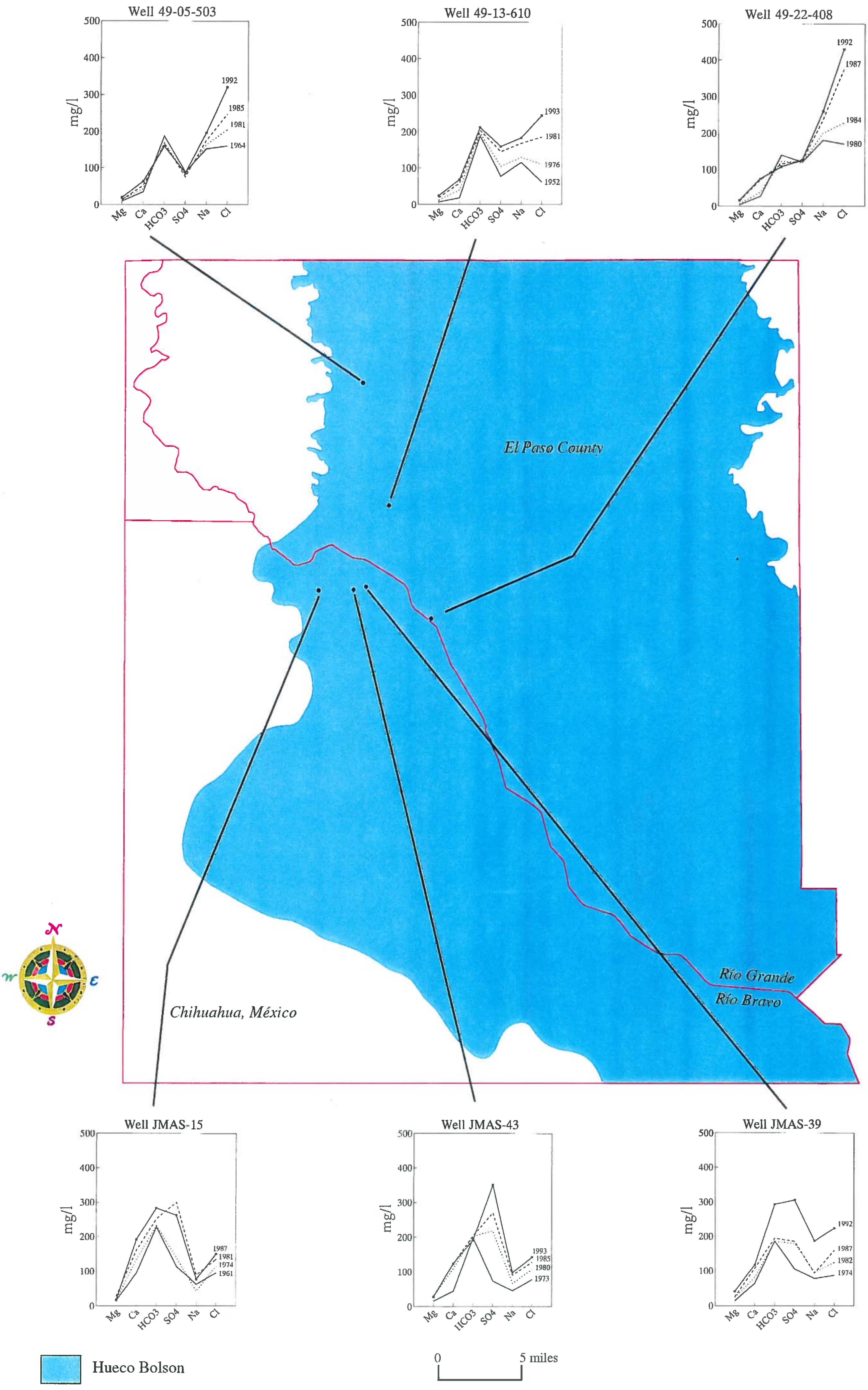
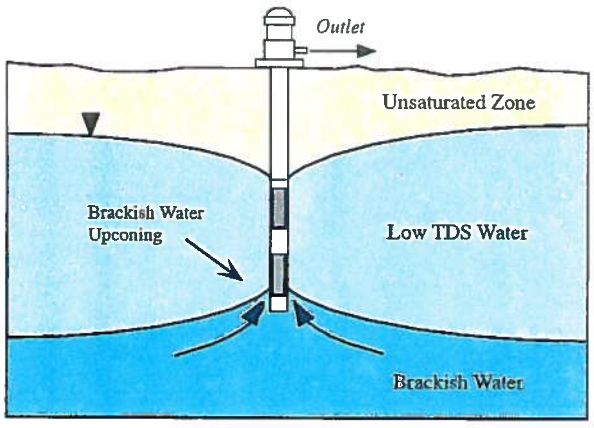
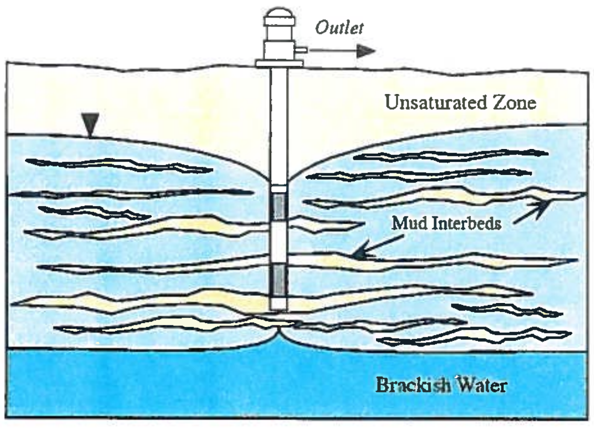


Figure 3.27 Time series hydrochemical plots for municipal wells in the City of El Paso and Ciudad Juarez area showing increasing concentrations of major elemental constituents in ground water (source of data, Texas Water Development Board; Junta Municipal de Agua y Saneamiento).



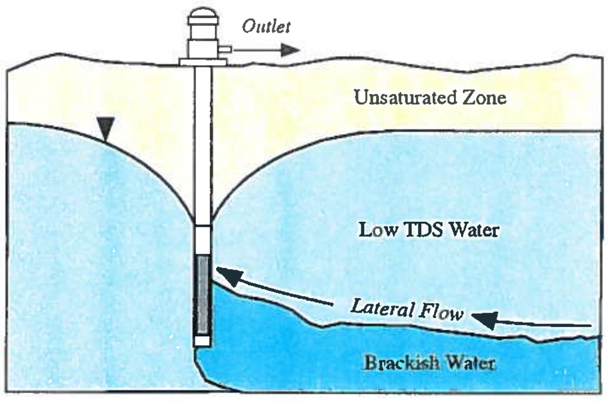
A

Upconing of saline water



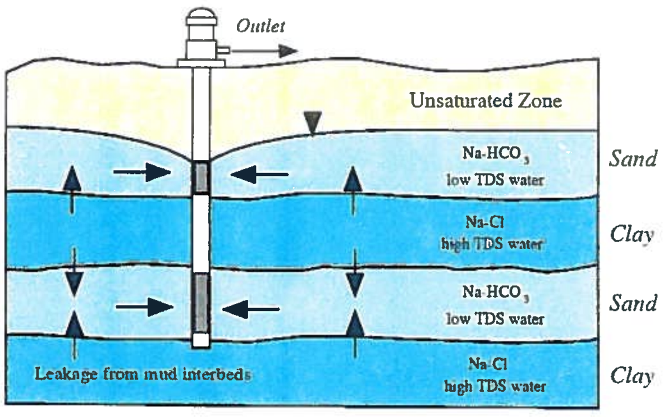
B

Mud interbeds may inhibit upconing



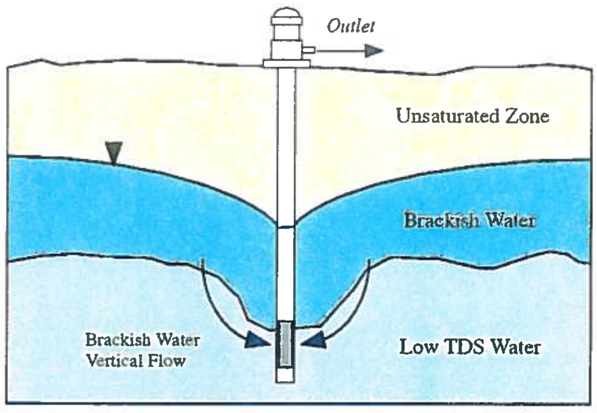
C

Pumping-induced lateral migration



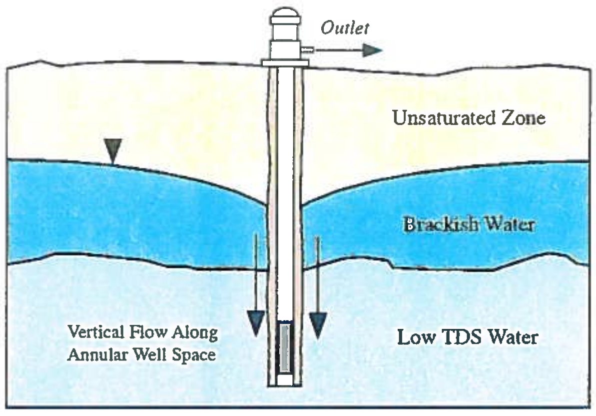
D

Leakage from mud interbeds



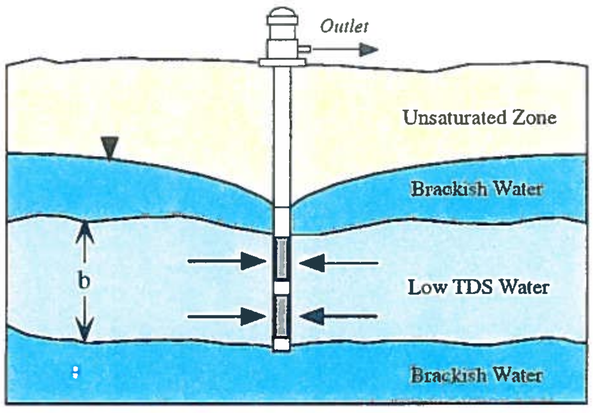
E

Downward movement through aquifer material



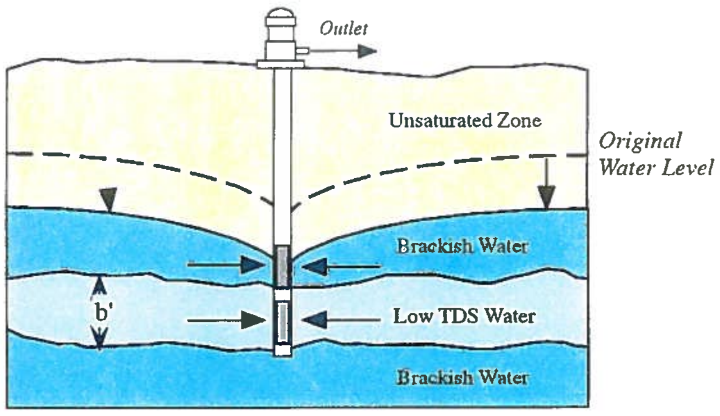
F

Downward movement along annular space



G

Thick freshwater layer...



H

...is depleted by pumping.

Figure 3.28. Possible sources of salinization of ground water in the City of El Paso/Ciudad Juarez area. Upconing has been proposed as a possible mechanism of salinization of water wells (a), but layered strata may minimize the effects of upconing (b). Salinization of water wells may occur as a result of lateral migration (c), or as a result of leakage from mud interbeds (d). Slightly more-dense brackish water may more easily move downward (e), especially along the annular space of a poorly constructed or abandoned well (f). Where saline ground water overlies and underlies a zone of freshwater (g), well salinization can occur as the freshwater lense is depleted due to long term pumpage (h).

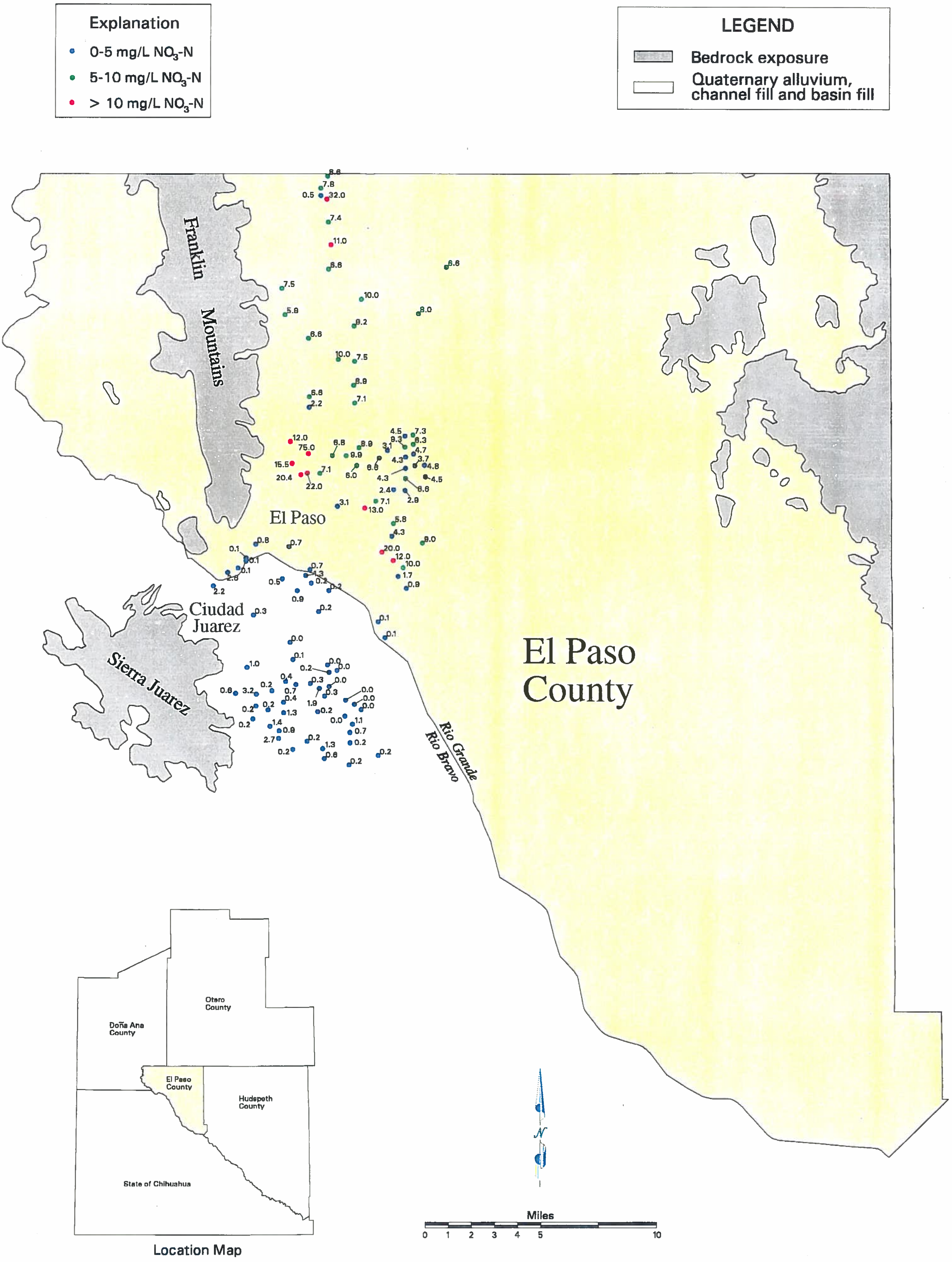


Figure 3.29. Nitrate concentrations in military, City of El Paso, and Ciudad Juarez municipal wells. All values reported as mg/L nitrate as nitrogen (NO_3–N). Data collected 1994 –1995 (source of data Texas Water Development Board; Junta Municipal de Agua y Saneamiento; City of El Paso Public Services Board).

Fecal Coliforms In Well Water

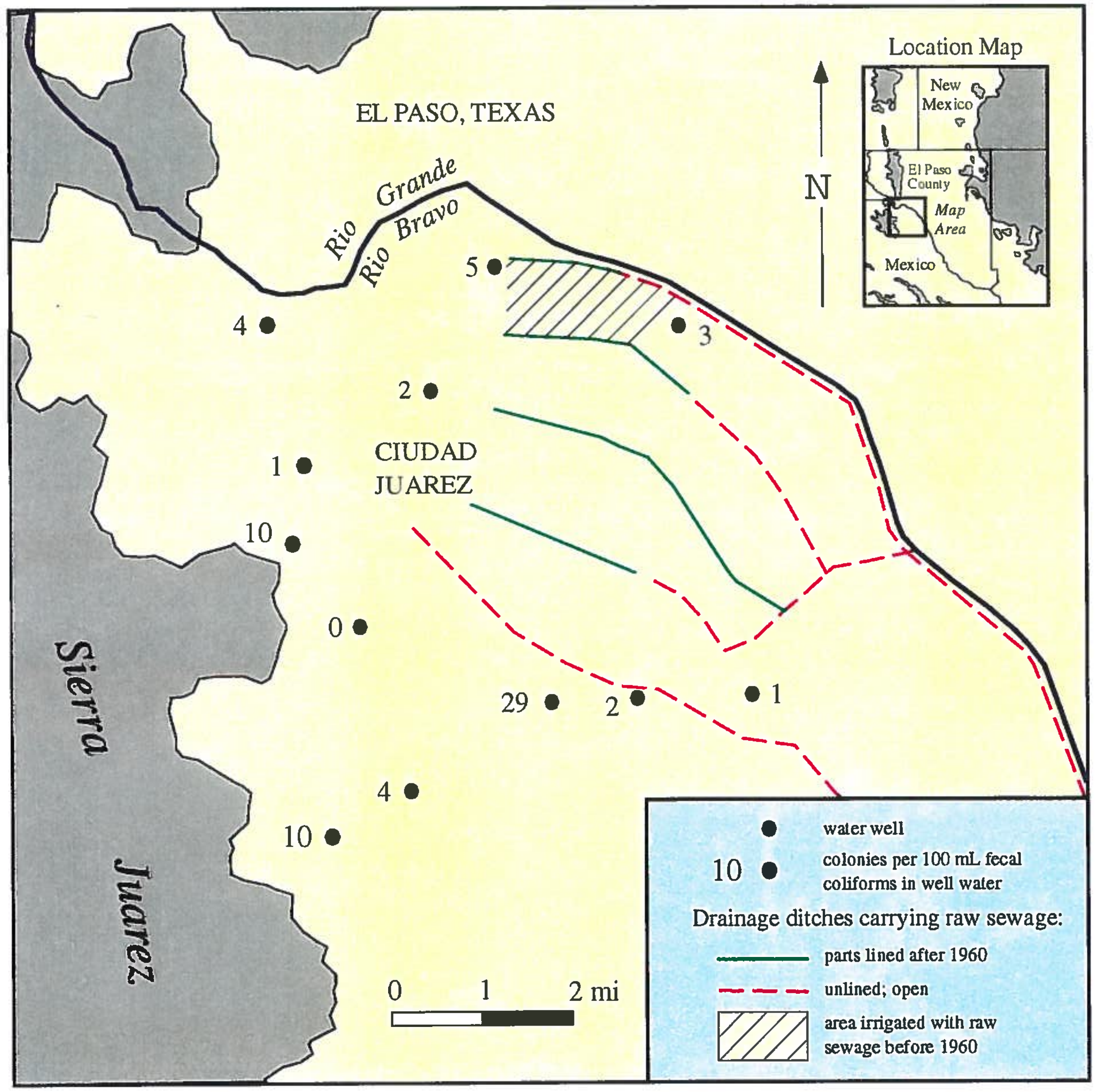


Figure 3.30. Diagram showing fecal coliform levels in 12 well-water samples collected in the Ciudad Juarez metropolitan area. These data were collected in 1987 (modified from Cech and Essman, 1992).

Blodgett, Texas Water Commission, personal communication).

In an earlier study, nitrate contamination was identified near El Paso's Old Mesa Well Field (White, 1987). Contamination probably occurred as a result of perched or shallow ground-water seepage into abandoned wells which recharge the deeper bolson aquifer (White, 1987). The abandoned wells act as conduits (Figure 3.28f) and allow shallow water to "cascade" into the deeper aquifer. Contamination was presumed to occur as a result of impounded urban runoff and deep percolation of commercial and residential lawn fertilizers.

Nitrate data collected between 1994 and 1995 indicate continuing nitrate problems in some parts of El Paso County. A cluster of wells in the vicinity of the Old Mesa Well Field in southwestern El Paso County exceed the 10 mg/L NO_3-N drinking water standard (Figure 3.29). Many of the samples in El Paso County tested between 5 and 10 mg/L NO_3-N. All of the wells in Ciudad Juarez and immediate vicinity are less than 5 mg/L NO_3-N (Figure 3.29).

In the Ciudad Juarez area, Cech and Essman (1992) tested residential water supplies in 1987 for possible contamination of ground water by sewage. They used fecal coliform as an indicator parameter. Forty-two samples were obtained; 30 from tap water and 12 from raw ground water. Ninety-one percent of raw groundwater samples were fecal coliform positive (Figure 3.30). Sixty percent of tap water samples were fecal coliform positive. The percentage of positive bacteria detections in these samples suggested that ground water beneath Ciudad Juarez was contaminated by sewage. These results may not be surprising because at the time of the sampling Ciudad Juarez had no sewage treatment facilities, and only 60% of the population was served by sewage lines (Figure 3.30). Sewage mains discharge into ditches (many of which are unlined and open) which carry the sewage to agricultural fields and into the Rio Grande (Cech and Essman, 1992).

Rio Grande waters are already contaminated above the El Paso/Ciudad Juarez metroplex. Contaminants include TDS, fecal coliforms, sulfates, and chlorides (Eaton and Anderson, 1987). Possible causes of these contaminants include irrigation return flows and municipal discharges. The quality of Rio Grande water deteriorates along the El Paso/Ciudad Juarez corridor and further downstream. Contamination is deduced by fecal bacteria as an indicator parameter. Immediately below El Paso, fecal coliforms as high as 290,500 colonies per 100 mL of water have been reported in Rio Grande water (Cech and Essman, 1992).

The exchange of water between the Rio Grande, the Rio Grande aquifer, and regional aquifers, such as the Hueco-Tularosa aquifer are explored in Chapter 5. Although the discussion deals primarily with salinity exchange, the fluxes present in these systems must be considered in light of possible anthropogenic pollutants that move from one water body to another.

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CHAPTER 4 - 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. A southeast trending linear feature, the bolson extends for 55 miles from the 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 La Amargosa, Sierra de San Jose Del Prisco, Sierra de Las Vacas, and Sierra de Carrizalillo define its southern boundary (Figure 4.1). Total surface area of the southeastern Hueco Bolson is 829 mi^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 4,600 to 3,600 ft near the Diablo Plateau escarpment and Quitman Mountains to elevations of 3,550 to 3,300 ft along the Rio Grande. South of the river, the floor of the bolson slopes from elevations of 4,450 to 4,100 ft along mountain fronts to the Rio Grande. The Rio Grande is the only perennial river between the El Paso/Hudspeth 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.

Stratigraphy and Water-Bearing Characteristics

Rock and sediment types

Saturated rocks in the highlands are recharged by precipitation (Figure 4.2). 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. Groundwater divides in the mountains and plateaus define the limits of basinward recharge areas and the geographical limits of the aquifer (Figure 4.1).

The principal hydrostratigraphic units in the southeastern Hueco aquifer are the carbonate and clastic rocks of the Cretaceous Finlay, Cox, and Bluff Mesa formations (Figure 4.3). These rocks 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 discontinous 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 (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 (Fisher and Mullican, 1990).

The thickness of the basin fill decreases from as much as 8,500 ft 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 of the Fort Hancock formation. Fort Hancock sediments are mostly lacustrine clay, bedded gypsum, and sand, silt, and clay from both alluvial fans and local fluvial deposits (Collins and Raney, 1991). The Camp Rice formation, a second major lithologic unit, is thin and contains little water east of the El Paso/Hudspeth county line. Camp Rice 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 older Fort Hancock deposits by an uncomformable contact as much as 2.5 m.y. old (Vanderhill, 1986).

The Quaternary alluvium and terrace deposits adjacent to the Rio Grande were formed by sediment deposition by the river. These deposits and their hydrogeologic characterstics are discussed in Chapter 5, entitled "Rio Grande aquifer." Cross-formational flow between the Rio Grande aquifer and older bolson deposits is discussed in this chapter (Figure 4.2), but other details are omitted until later.

Aquifer properties

Transmissivity values in the Cretaceous strata and bolson fill north of the Rio Grande are all relatively low (Table 4.1). Well yields do not exceed 200 gpm usually and most well yields are less than 50 gpm.

Aquifer tests performed in wells screened or open in Cretaceous strata gave transmissivity values between 0.22 and 1.50 ft^2/day (Mullican and Senger, 1992). These estimates were derived from wells concentrated about the southwestern Diablo Plateau. Aquifer tests in Cretaceous rocks on the northeastern Diablo Plateau gave higher average transmissivity values (see Chapter 6), between 0.32 and 6,700 ft^2/d (Kreitler and others, 1986). Wells to the northeast are located along regional flexures and may have higher transmissivity values due to greater density of fractures.

Aquifer tests in wells completed in bolson silts and sands gave transmissivity estimates between 0.43 and 94 ft^2/day (Mullican and Senger, 1992). Higher transmissivity values are characteristic of a higher percentage of sand and gravel in the basin (Table 4.1). Lower transmissivity values are characteristic of mud-rich sediments deposited in lacustrine and playa environments. Aquifer tests in basin fill indicate relatively low transmissivity values, sufficient only for livestock and domestic use.

We could not locate aquifer test data in the Mexican part of the southeastern Hueco aquifer; few if any may exist. There are at least 100 documented wells that draw water, at least in part, from bolson silts and sands (IBWC, 1989). Many of these are irrigation wells and most are aligned marginal to or on the Rio Grande floodplain (IBWC, 1989).

Many wells are concentrated about the larger arroyos. Arroyo deposits are coarse-textured and are surfaces for precipitation recharge. Placement of wells about arroyos provides a better chance of obtaining a prolific well with good quality water. Clayey-silts are dominant in the older basin fill and the few permeable sand-and-gravel lenses are usually saturated with saline water (Geo Fimex, 1970); not a good prospect for groundwater exploration and development.

That the density of wells at distances from arroyos is spotty provides indirect evidence of lower transmissivity values in the older basin fill. More credible evidence is provided by surface electrical resistivity sounding data (Geo Fimex, 1970). Vertical electrical soundings performed in the Mexican part of the southeastern Hueco Bolson showed that aquifer resistivities are usually less than 10 ohm-m (Figure 4.4). Such low values imply limited potential for development of well fields (Dobrin, 1976; Kearey and Brooks, 1984). Yields should be sufficient in most areas only to satisfy very limited agricultural and municipal water demands. Transmissivity values for saturated bolson fill in Mexico are probably similar to estimates derived in the American part of the southeastern Hueco Bolson.

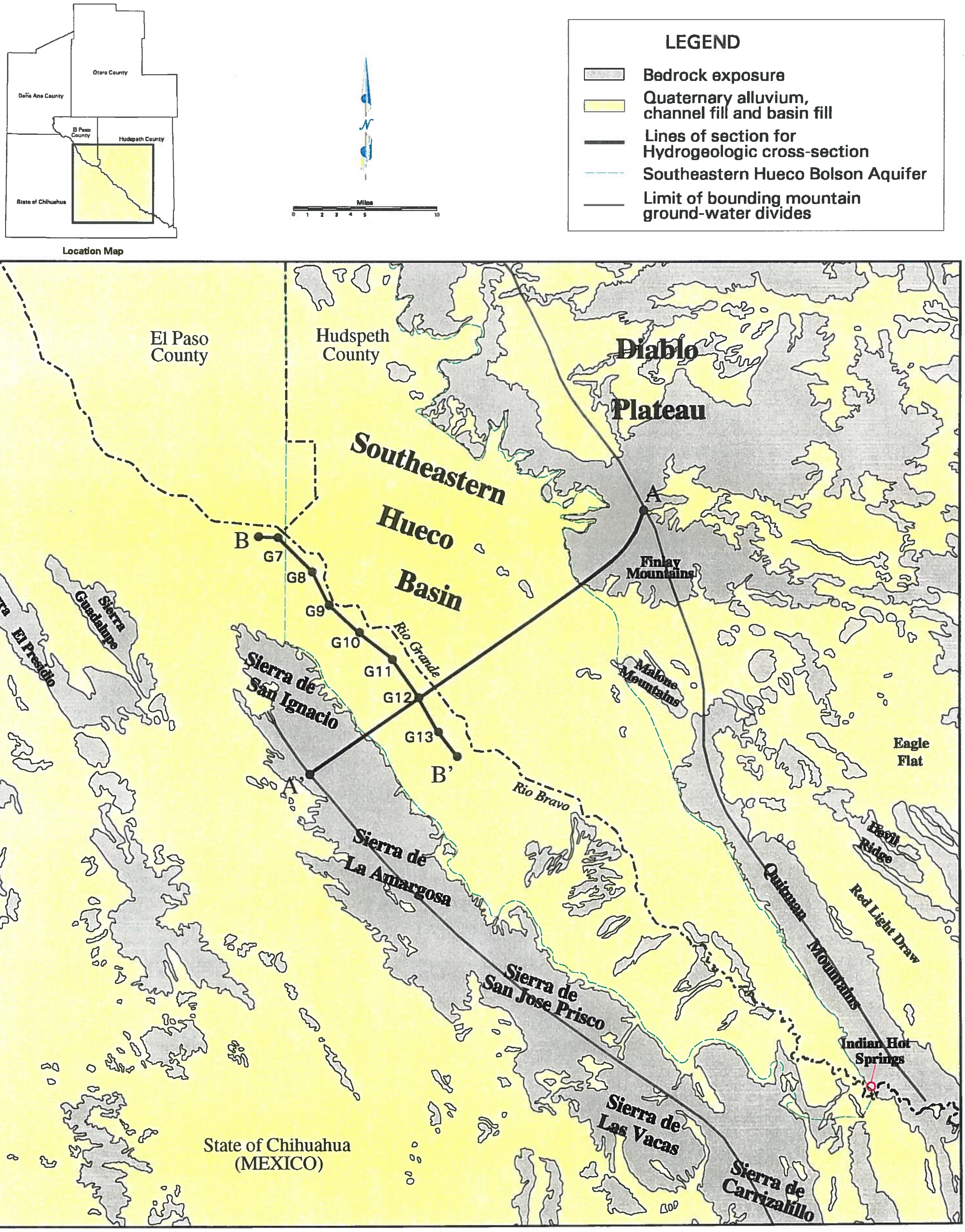

Figure 4.1. Location and extent of the southeastern Hueco aquifer. Map shows the limits of the southeastern Hueco Bolson aquifer as well as the limits of the bounding mountain ground-water divides that define the full extent of the aquifer (bolson fill and flanking highlands).

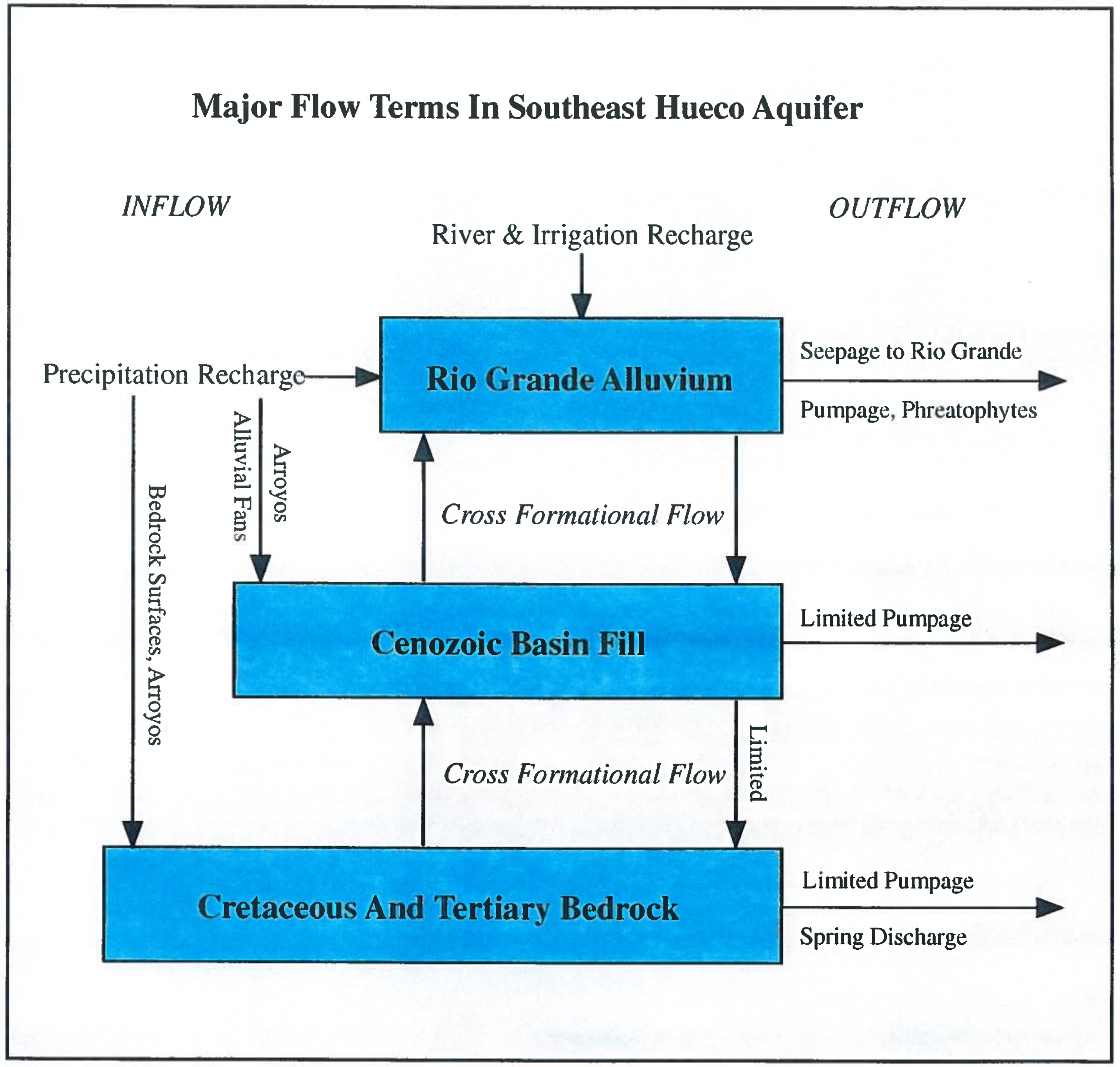

Figure 4.2. Major flow components in the southeastern Hueco aquifer.

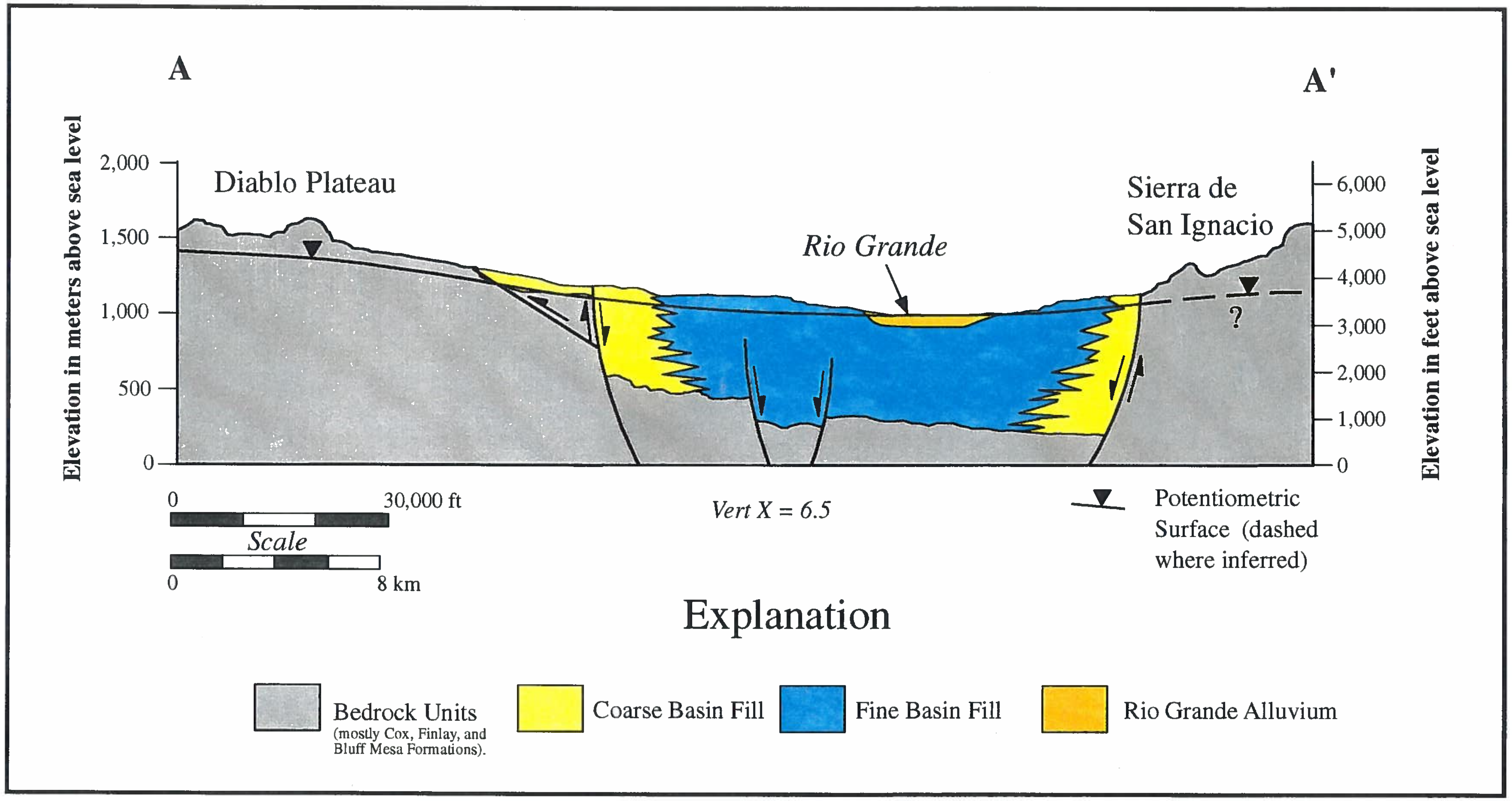

Figure 4.3. Generalized hydrogeologic cross section A - A' (line of section shown in Figure 4.1. Basin fill/bedrock contact selected from maps prepared by Collins and Raney, 1991, and from test-hole logs and geophysical logs in the Texas Water Development Board files).

Geoelectric Cross Section B - B'

Juarez Valley, Chihuahua Mexico

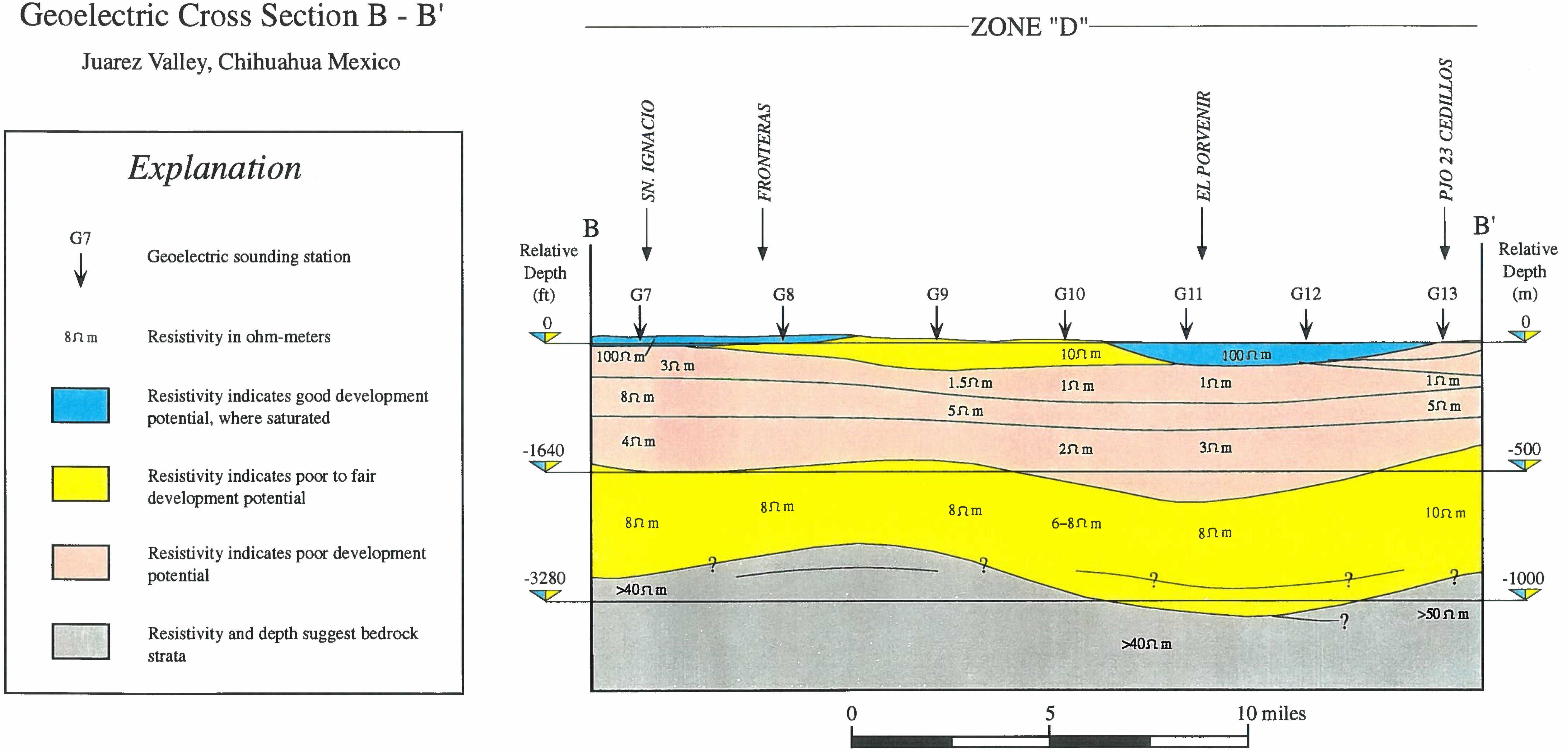

Figure 4.4. Geoelectric cross section B - B' across the southeastern Hueco aquifer, northern Chihuahua, Mexico. The map shows interpreted average real resistivities (modified from Geo Fimex, 1970; line of section shown on Figure 4.1).

Transmissivity Results From Aquifer Tests In The Southeastern Hueco Aquifer

State Well Number	Water Bearing Strata	Transmissivity (ft^2/day)	Aquifer Test Method
48-35-702	Cretaceous	0.22	Theis Recovery (semilog)
48-43-101	Cretaceous	0.60	Theis Recovery (semilog)
48-43-501	Cretaceous	1.50	Theis Recovery (semilog)
48-34-903	Hueco Bolson	94.0	Theis Recovery (semilog)
48-42-501	Hueco Bolson	3.60	Theis Recovery (semilog)
48-34-802	Hueco Bolson	0.43	Theis Recovery (semilog)
48-42-101	Hueco Bolson	3.60	Ferris and Knowles (slug)
48-35-701	Hueco Bolson	7.83	Ferris and Knowles (slug)

Table 4.1 Transmissivity values derived from aquifer tests in the southeastern Hueco Aquifer (data from Mullican and Senger, 1992)

Potentiometric Surface Map and 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 4.5). Areas of high hydraulic 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 head gradients in the bolson fill are about 0.008. Steeper hydraulic head gradients along mountain fronts are due to; (1) higher recharge rates in the mountains and along mountain fronts, and (2) average permeabilities of bedrock strata that are lower than average permeabilities of bolson fill (Table 4.1). By Darcy's law a high permeability material, allowing the same quantity of water to be transmitted as a low permeability material, has a smaller loss of hydraulic head along a flowpath vector.

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 the mountains in Mexico.

Depth to ground water in the southeastern Hueco aquifer is variable. The depths measured to the regional water table in Cretaceous rocks on the U.S. side varied from 76 to 627 ft, 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 93 and 479 ft (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, except in wells in the Rio Grande alluvium (see Chapter 5). Water-levels over the last few decades probably haven't changed significantly in the aquifer.

Ground-Water Availability

Estimates of the quantify of fresh and slightly saline water for the southeastern Hueco aquifer cannot be derived because lithologic, geophysical, and water quality data are not sufficient to permit analysis. Total quantity of fresh, slightly saline, and moderately-to-highly saline ground water in the bolson fill is estimated by calculating the volume of saturated fill between the water table and bedrock surface and by multiplying this volume by 0.22, an average specific yield value for the bolson fill. Total amount of water stored in the bolson fill is about 76 million acre-ft. Of this amount, 42 million acre-ft are stored in the American part of the southeastern Hueco Bolson and 34 million acre-ft are stored in the Mexican part of the bolson.

The estimates for Mexico are less reliable because the water table map and bedrock configuration map were developed with fewer data. The analysis ignores the amount of water held in artesian storage (negligible compared to the drainage porosity) and does not include water stored in Cretaceous and Tertiary bedrock aquifers.

Recharge Areas

Tritium (^{3}H) and carbon-14 (^{14}C) data provide clues to the distribution of recharge and relative ages of ground water. Pre-1950 values for tritium in northern hemisphere precipitation were about 5 tritium units (TU), where one TU is equal to one atom of ^{3}H in 10^{18} atoms of hydrogen. Tritium has a half life of 12.3 years (Mazor, 1991) and ^{3}H values less than about 0.5 TU usually indicate ground waters recharged before 1952, provided that extensive dilution by older ground waters has not occurred (Mazor, 1991). Tritium in northern hemisphere precipitation increased to more than 2,000 TU as a result of above-ground testing programs for nuclear weapons in the 1950's and 1960's. Tritium has decreased to near-background levels in recent years (Mazor, 1991).

With a much longer half-life of 5,730 years, ^{14}C is a radiometric dating tool that may be used to date ground water to 30,000 years or more provided appropriate adjustments are made to account for factors other than radiometric decay (i.e., mixing and/or isotope exchange) that alter the original isotopic signatures (Fontes and Garnier, 1979; Mook, 1980). The results of ^{14}C analyses are usually reported in units of percent modern carbon (pmc). In the ideal case, an initial ^{14}C concentration of 100 pmc in ground water, a parcel of 50 pmc ground water that has not undergone mixing or dilution is 5,730 years old. The carbon cycle is seldom ideal and rock in carbonate terrains may have an initial value of 60 ± 5% pmc due to rock-water and soil-water interactions in the vadose zone (Mazor, 1991). Initial values greater than 100 pmc in non-carbonate rocks (Fontes and Garnier, 1979; Mazor, 1991) are due to enhanced ^{14}C production associated with above-ground nuclear weapons testing programs of the 1950's and 1960's. Such irregularities require identification of the stable carbon-isotope signature of rock, among other data, for correction factors to be applied.

We use published radioisotope data to identify recharge areas and relative ground-water residence times (Fisher and Mullican, 1990). We do not attempt to derive adjusted ^{14}C ages because of uncertainty regarding many factors known to influence the chemistry of dissolved inorganic carbon in ground water (Fontes and Garnier, 1979; Mook, 1980). The complex tectonic history of the region and juxtaposition of rocks of different lithologies and ages make application of correction techniques to the ground water in the area difficult. The absolute values of ^{14}C are used to provide information about the relative differences in ground-water ages within the basin and as an indicator of the areas where recharge occurs.

Radioisotope data and water-level information indicate that precipitation recharge to the basins occurs primarily within the upper mountains and plateaus, and across the broad alluvial fans that border mountain fronts (Figure 4.6). The data indicate there is a clearly defined trend toward lower ^{14}C and tritium within basin floor areas in the southeastern Hueco aquifer. Plots of ^{3}H and ^{14}C versus surface elevation suggest mixing of waters of different ages within the basin (Figure 4.6). Low percentages of modern carbon and tritium activities above 0.5 TU units in alluvial fans imply mixing of young and old ground water at the fans. Ground water moving downgradient from the mountains may converge at the fans and mix with recent precipitation recharge on the fans.

Major arroyos dissect the alluvial fans and bolson surfaces in the southeastern Hueco aquifer, sometimes penetrating the underlying Cretaceous rocks. These arroyos, sometimes over 200 ft wide, convey substantial quantities of runoff during episodic wet years and act as a third pathway for focused recharge downgradient from the principal recharge surfaces in the Diablo Plateau and alluvial fans.

Discharge Areas

Ground water is lost from the southeastern Hueco aquifer by spring discharge and by cross-formational leakage to the Rio Grande alluvium (Figure 4.2). Well discharge accounts for limited discharge from the basin except in the Rio Grande alluvium where irrigated agriculture is common.

Two hot springs (Indian Hot Springs and Red Bull Spring) are located near the southwestern end of the Quitman mountains along the trace of the Caballo

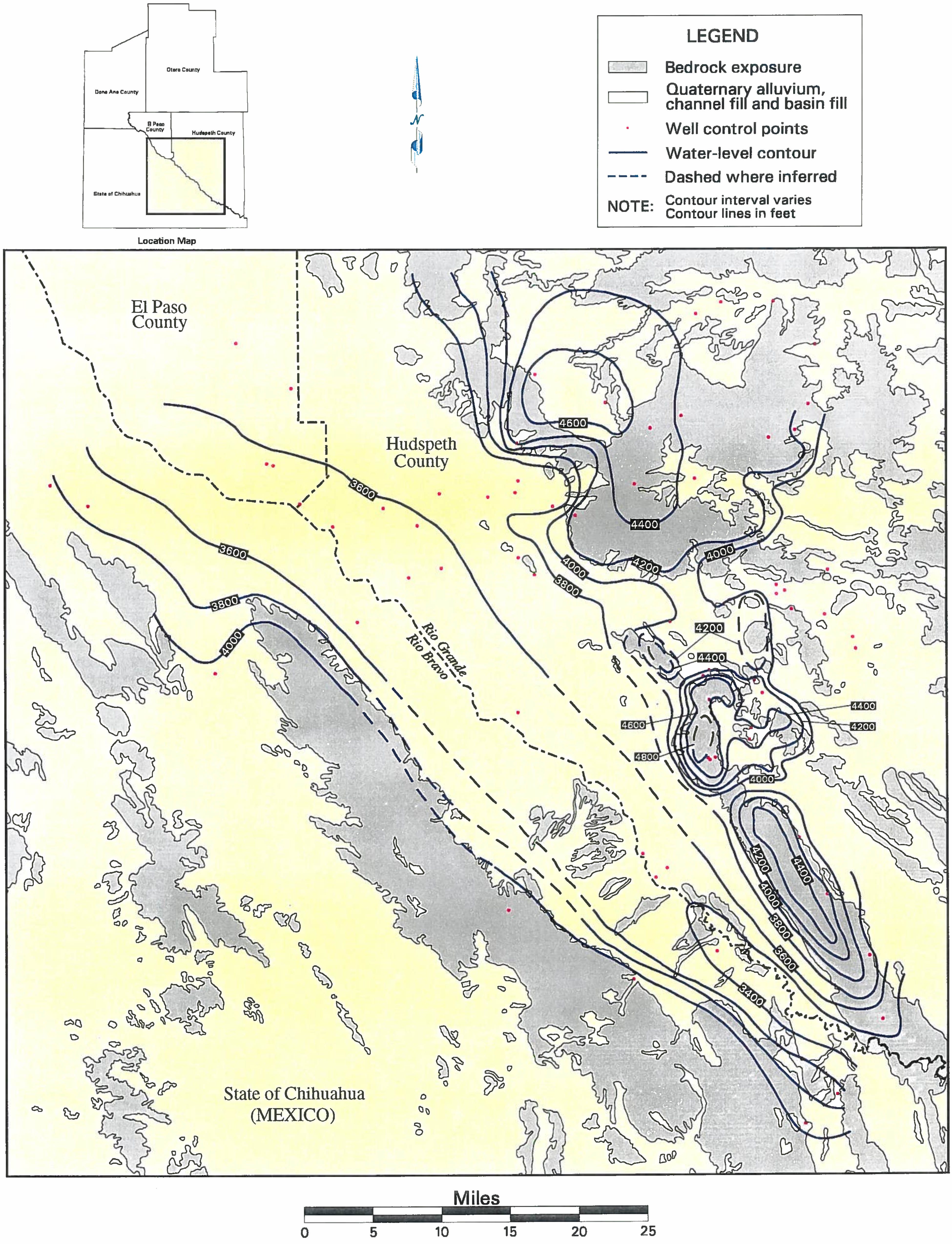

Figure 4.5. Regional potentiometric surface map for the southeastern Hueco aquifer and surrounding mountains and plateaus.(source of data, Fisher and Mullican, 1990; Texas Water Development Board; Comision Nacional del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

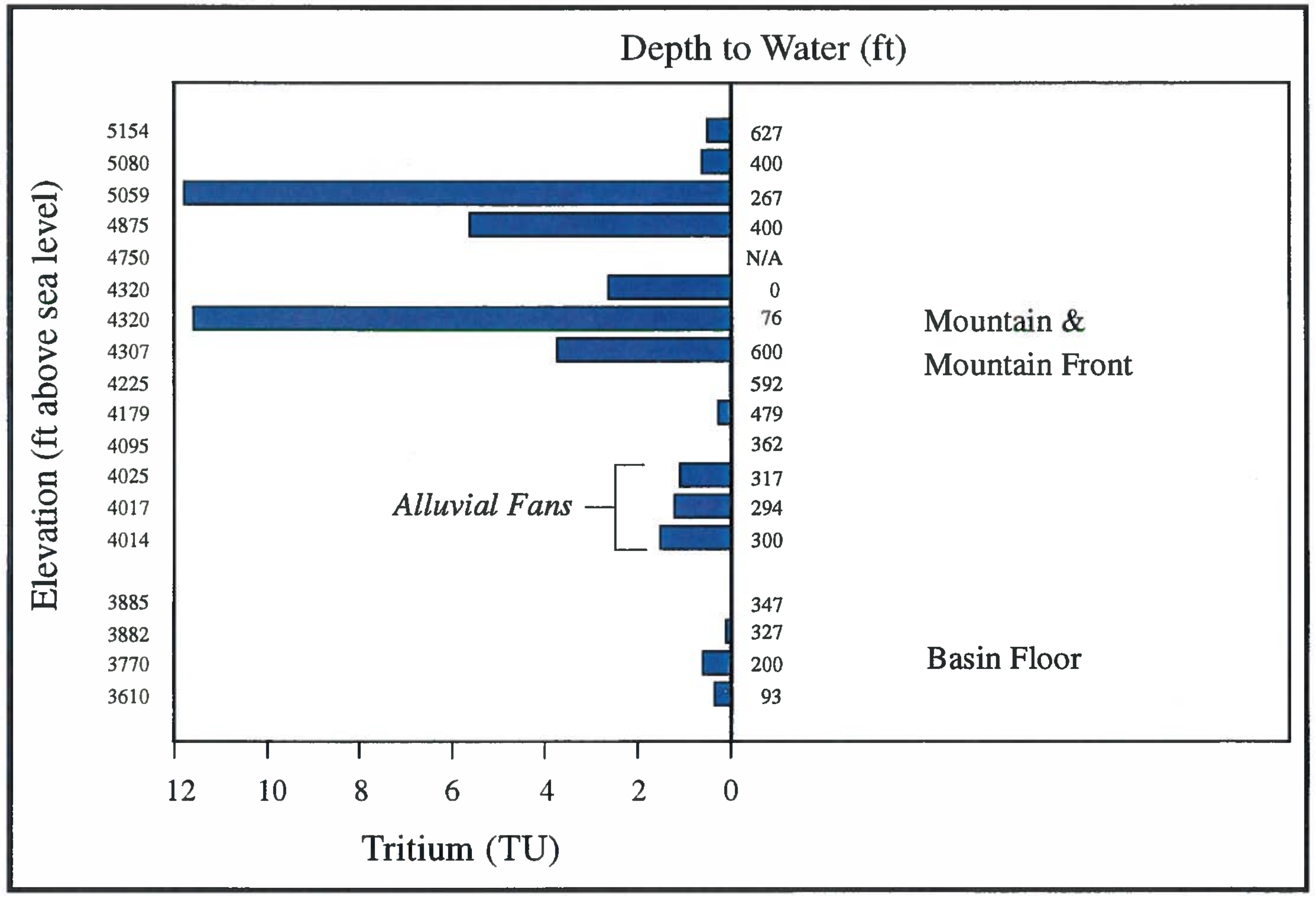

Figure 4.6a. Tritium activities (TU) in highland (mountain and mountain front) and lowland (basin floor) areas of the southeastern Hueco aquifer indicate that precipitation recharge occurs primarily within the upper mountains and plateaus (source of data, Fisher and Mullican, 1990).

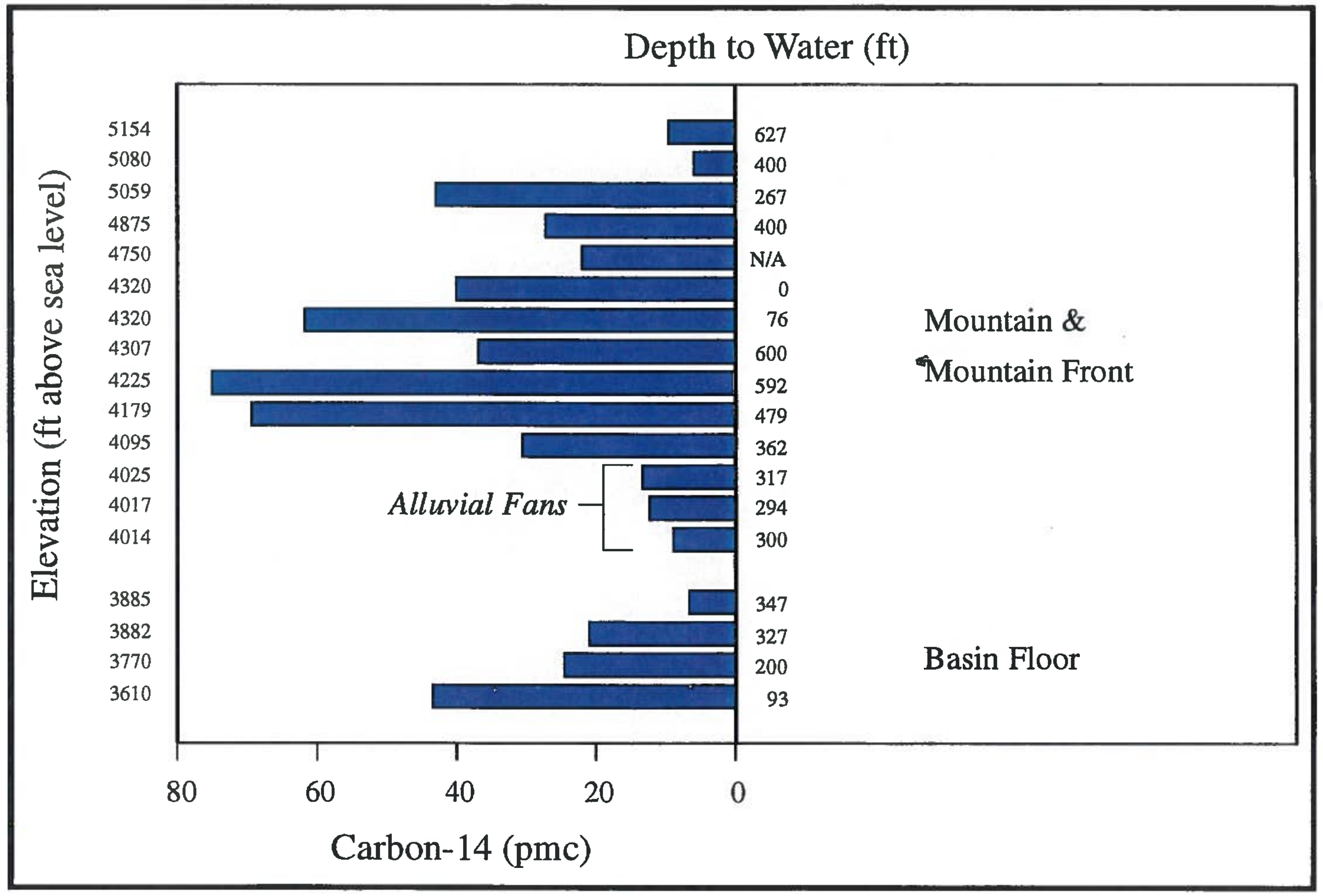

Figure 4.6b. Percentages of carbon-14 in highland (mountain and mountain front) and lowland (basin floor) areas of the southeastern Hueco aquifer indicate that precipitation recharge occurs primarily within the upper mountains and plateaus (source of data, Fisher and Mullican, 1990).

Fault, a northwest-trending normal fault that separates the Quitman Mountains and the southeastern Hueco Bolson. Water temperatures in the hot springs vary from 27 to 50°C (Darling and other, 1994). Several small, cooler springs are located in the Mexican part of the aquifer, mostly along faults in the highlands. Temperature in these springs vary from 22 to 25°C.

Cool springs are usually discharge areas for local ground-water flow systems (Mifflin, 1988). Temperature and discharge in springs that issue water from local flow systems are susceptible to large fluctuations due to changes in atmospheric temperature and moisture. Hot springs are usually discharge areas for regional flow systems. Temperature and discharge from hot springs in regional flow systems tend to vary only slightly from year to year (Mifflin, 1968; Winograd and Thordarson, 1975).

Most of the ground-water discharge from the southeastern Hueco aquifer occurs by cross-formational leakage to the Rio Grande alluvium (Figure 4.2). This ground water, in turn, eventually leaks into the Rio Grande or is discharged by well pumping from the alluvium. Consumptive use by phreatophytes accounts for another component of discharge (Figure 4.2). Salt cedar are densely thicketted in the Rio Grande alluvium below Fort Quitman and account for significant ground-water consumption along this stream reach.

Water Quality

General hydrochemistry

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 Chapter 5.

The hydrochemical facies (Back, 1966) of southeastern Hueco aquifer ground waters on the American side of the study area (Figure 4.7) varies from Ca-Mg-HCO_3 and Na-SO_4 along the Diablo Plateau to Na-SO_4-Cl beneath the floor of the basin. South of the Rio Grande, ground waters vary from Ca-Mg-HCO_3 beneath the mountain ranges to Ca-Mg-SO_4-Cl waters beneath the basin floor (Figure 4.7). Typically these ground waters have TDS that vary between 1,000 and 3,500 TDS. 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.

Origin of solutes

Hydrochemical signatures within the southeastern Hueco aquifer are controlled by the solubilities of aquifer materials, cation exchange, and simple mixing. The concentrations of Ca, Mg, and Na, for example, are controlled by weathering of carbonates, gypsum, and halite and by exchange of the divalent cations Ca and Mg for the monovalent cation Na (Fisher and Mullican, 1990; Darling and others, 1994). Slightly saline ground waters are dominated by the dissolution of gypsum whereas dilute ground waters are dominated by the dissolution of calcite and dolomite. Halite dissolution is indicated for moderately saline water at Indian Hot Springs by a plot of the molar ratio of (Na/Cl) against the concentration of Cl (Figure 4.8). (Na/Cl) molar ratios approach a value near 1.0 at Indian Hot Springs and usually range from 2.0 to as much 7.0 in more dilute waters (Figure 4.8). Ratios near 1.0 are the result of the release of equimolar concentrations of Na and Cl by dissolution of halite.

The molar ratio of chloride to bromide (Cl/Br) offers further support for halite dissolution as a significant control on hydrochemical compositions at Indian Hot Springs (Figure 4.9). These ratios are less than 750 in the southeastern Hueco aquifer and more than 3,000 at Indian Hot Springs. Chloride-bromide (Cl/Br) ratios reflect the origin of water as marine (-300 - 650), as a second-cycle solution of marine salt (>1,000), or as a residual brine from precipitation of halite (< 250; Holser, 1979; Darling and others, 1994). The (Cl/Br) ratio of sea water remains nearly constant during evaporation up to the concentration at which halite precipitates (Holser, 1979; Drever, 1988). The larger bromide ion is preferentially excluded from the halite lattice structure during precipitation, and residual brine is consequently enriched in Br relative to Cl ([Cl/Br] ratio decreases) while halite is deficient in Br (Darling and others, 1994). The (Cl/Br) ratios of circulating meteoric ground water can increase by several factors as large masses of halite are dissolved, as indicated at Indian Hot Springs.

Within SO_4 - dominated waters, the predominant source of excess sodium is cation exchange with Ca the primary exchangeable divalent cation (Fisher and Mullican, 1990). Within HCO_3 waters, the dissolution of carbonate rocks provides most of the Ca required to drive the exchange. Subtracting the molar concentration of Cl from Na yields an estimate of the mass of Na attributable to the dissolution of halite (Na-Cl). A plot of (Na-Cl) against SO_4 produces a trend with a slope of approximately 2.0 in ground water north of the Rio Grande, a ratio expected in a 2 to 1 exchange of Ca for Na (Figure 4.10).

In summary, the origin of dilute and slightly saline ground waters in the southeastern Hueco aquifer corresponds to a set of common geochemical reactions, including dissolution of calcite, dolomite, gypsum, and simple cation exchange (Fisher and Mullican, 1990). These simple reactions are explained by the predominance of carbonate, evaporite, and clay minerals in Cretaceous rocks and basin fill, and by the tendency for exchange of bound sodium for calcium in solution, the dominant ion exchange reaction in dilute waters (Drever, 1988).

The geochemical signature of halite dissolution on the waters at Indian Hot Springs is more problematical, as no large halite deposits are found north of the Rio Grande. Halite deposits are ubiquitous in the area south of the Rio Grande however. El Cuervo Bolson, located 25 miles southeast of Indian Hot Springs, is underlain by thick evaporite assemblages consisting of halite, gypsum, and anhydrite. This bolson aquifer is connected to Indian Hot Springs by a series of northwest trending faults and fractures in the Texas lineament and may be a source of warm and moderately saline ground water that discharges at the springs (Hibbs and Jones, 1996).

Ground-Water Movement

Numerical flow modeling

An important goal of this project is to identify areas where ground water moves, or may move across the international boundary. Transboundary ground-water flow is a sensitive international issues because the southeastern Hueco aquifer is adjacent to northwest Eagle Flat, the host basin for disposal of interstate sludge. Northwest Eagle Flat is also the proposed basin for disposal of low-level radioactive waste (Darling and others, 1994).

Ground-water movement across the international border could carry contaminants from one country to the other. A numerical profile model and pathline simulator are devised to predict potential transboundary ground-water flow. The model is used to predict ground-water residence times, ground-water pathlines, and the recharge rate that will bring the aquifer to flow capacity

Model orientation and design

The two-dimensional, cross-sectional model is developed along a 30 mile transboundary flowline oriented between the Diablo Plateau and the Sierra de San Ignacio (Figures 4.1 and 4.3). The steady-state model consists of 30 layers and 92 columns (Figure 4.11). Each of the 2,760 cells is 150 ft high by 1716 ft long. Boundary conditions were selected to correspond closely to actual hydrologic boundaries (Figure 4.11). A no-flow boundary was established at a depth of 100 ft below sea level at the brine/brackish water interface.

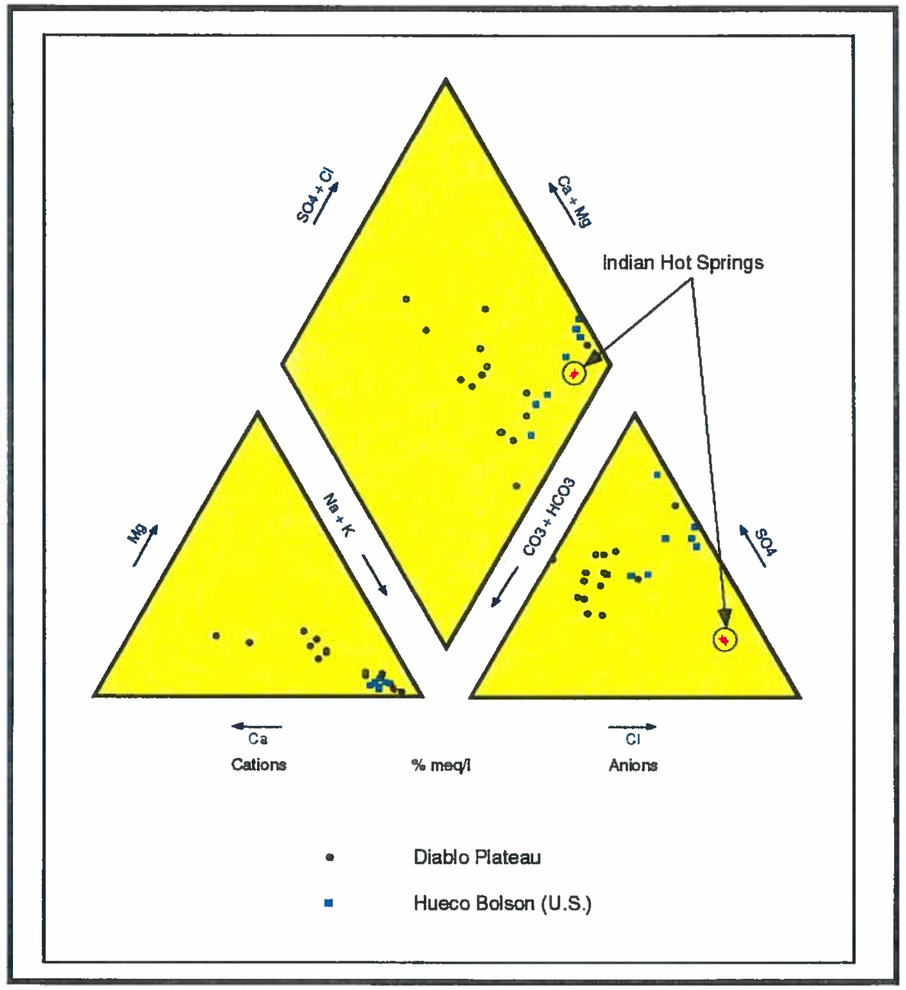

Figure 4.7a. Hydrochemical Piper plot for the bedrock (mountain and plateau) strata, bolson strata, and Indian Hot Springs in the U.S. part of the southeastern Hueco aquifer. Piper plot indicates distinct hydrochemical types for these water bearing strata in the southeastern Hueco aquifer (source of data, Fisher and Mullican, 1990; Texas Water Development Board).

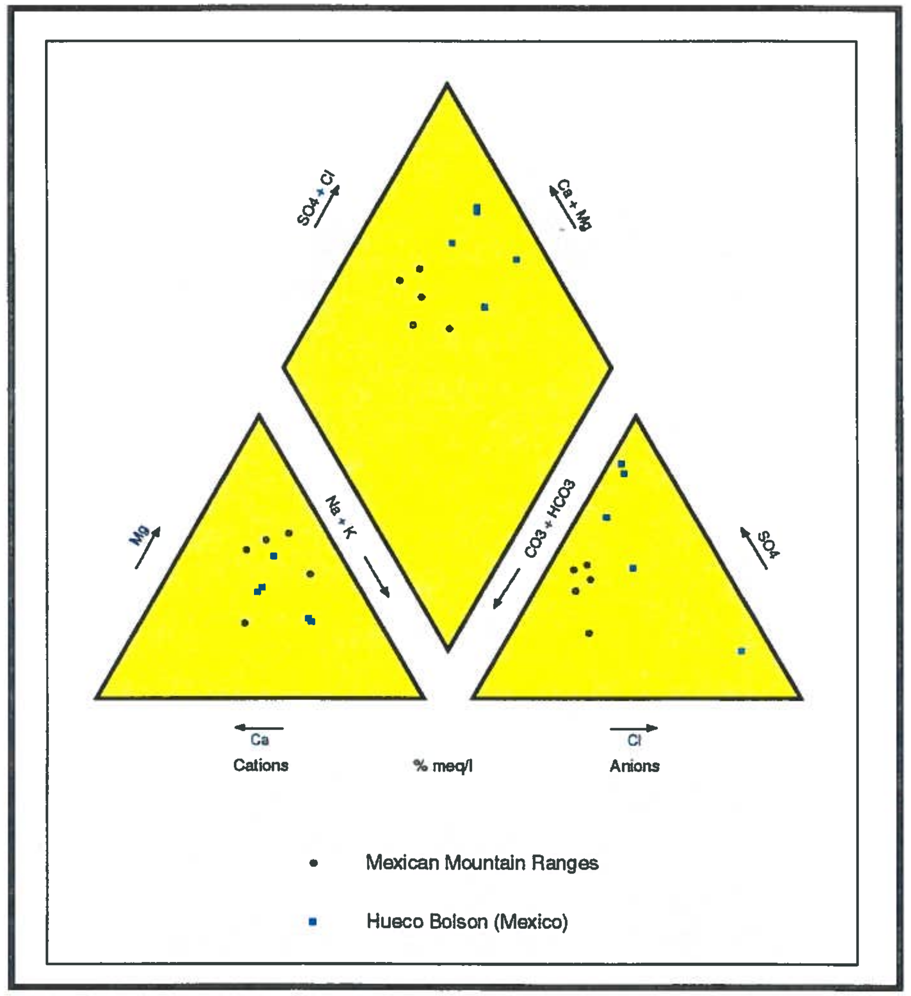

Figure 4.7b. Hydrochemical Piper plot for the bedrock (mountain) strata and bolson strata in the Mexican part of the southeastern Hueco aquifer. Piper plot indicates distinct hydrochemical types for these water bearing strata in the southeastern Hueco aquifer (source of data, Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

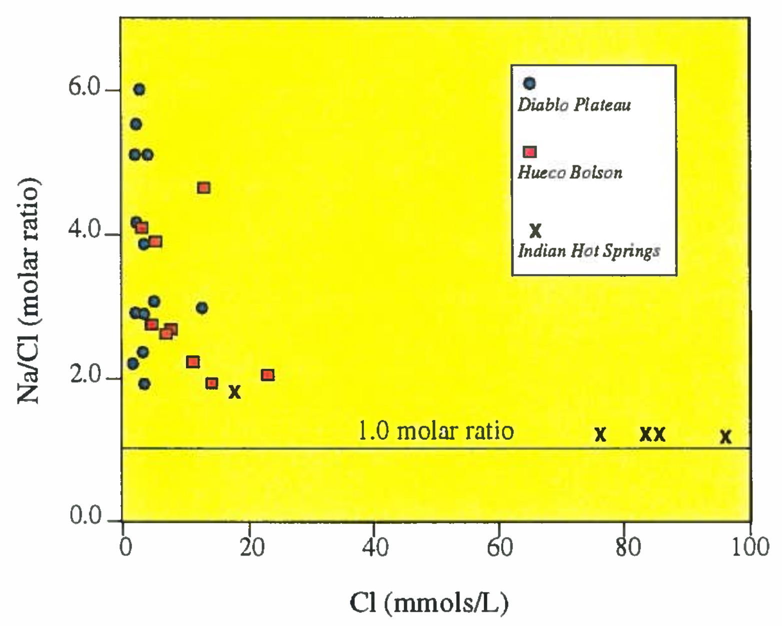

Figure 4.8a. Scatter plot showing (Na/Cl) molar ratios vs molar Cl for samples collected from bedrock strata, bolson strata, and Indian Hot Springs, U.S. (source of data, Fisher and Mullican, 1990; Darling and others, 1994; Texas Water Development Board).

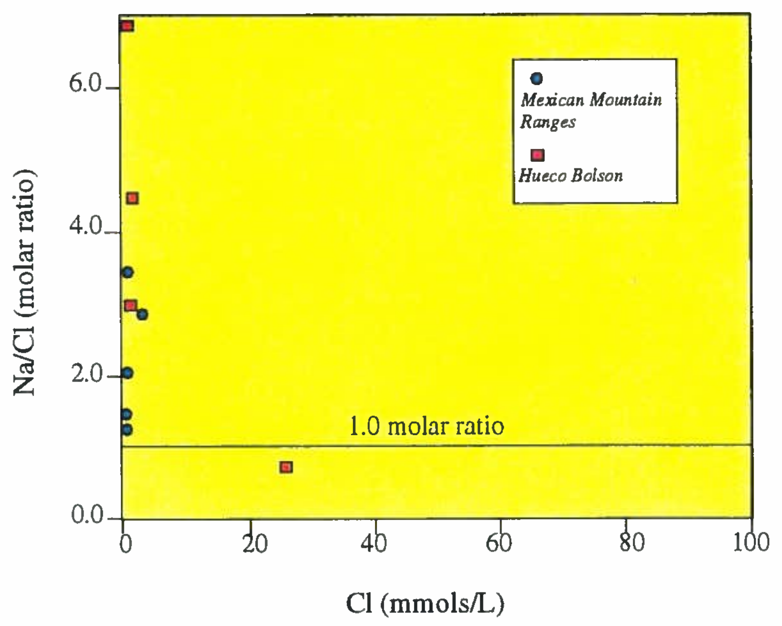

Figure 4.8b. Scatter plot showing (Na/Cl) molar ratios vs molar Cl for samples collected from bedrock strata and bolson strata, Mexico (source of data, Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

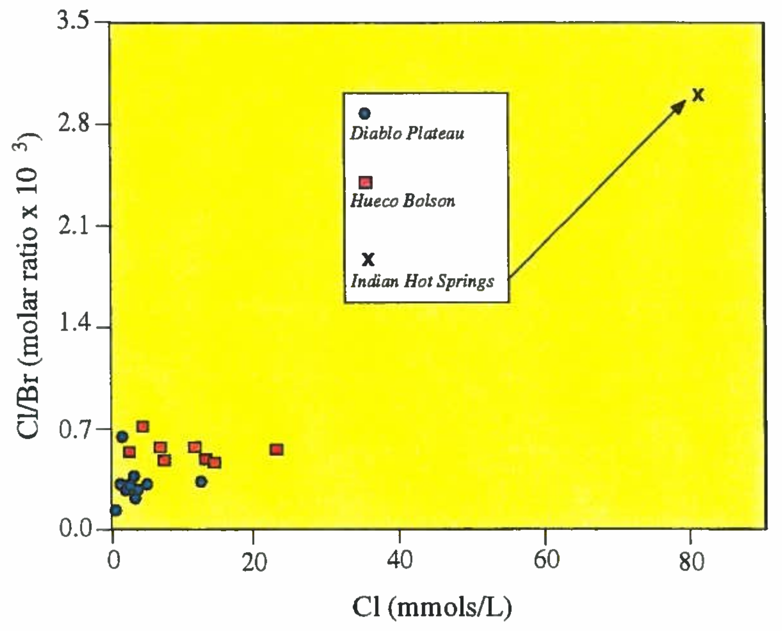

Figure 4.9. Scatter plot showing (Cl/Br) molar ratios vs molar Cl for samples collected from bedrock strata, bolson strata, and Indian Hot Springs, U.S. (source of data, Fisher and Mullican, 1990; Darling and others, 1994; Texas Water Development Board).

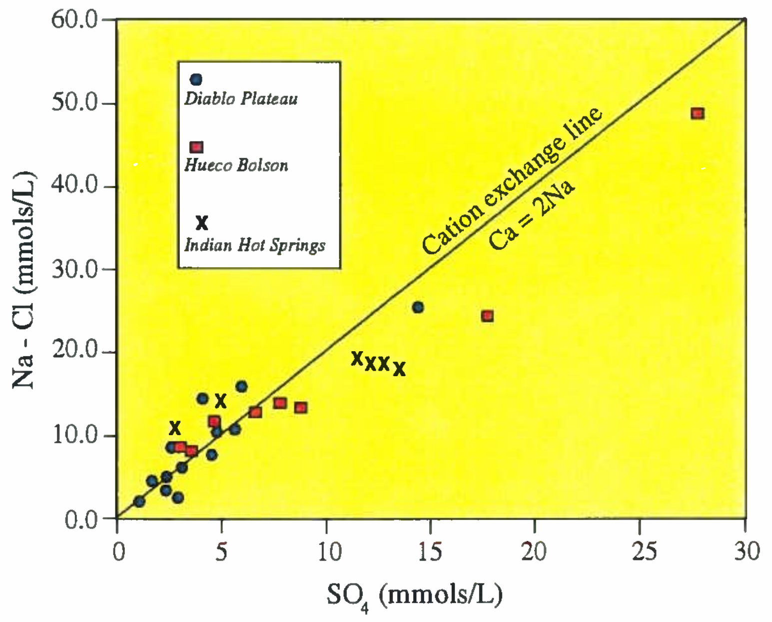

Figure 4.10a. Scatter plot showing (Na - Cl) molar quantity vs molar SO₄ for samples collected from bedrock strata, bolson strata, and Indian Hot Springs, U.S. (source of data, Fisher and Mullican, 1990; Darling and others, 1994; Texas Water Development Board).

Figures 4.8 through 4.10 show a series of scatter plots for ions in the ground water of the southeastern Hueco aquifer. Plots shown for the saturated basin fill in both the United States (Figures 4.8a, 4.9, and 4.10a) and Mexico (Figures 4.8b and 4.10b), and for the bedrock aquifers that are located in the flanking highlands. Indian Hot Springs waters plot distinct from other ground waters represented in these plots.

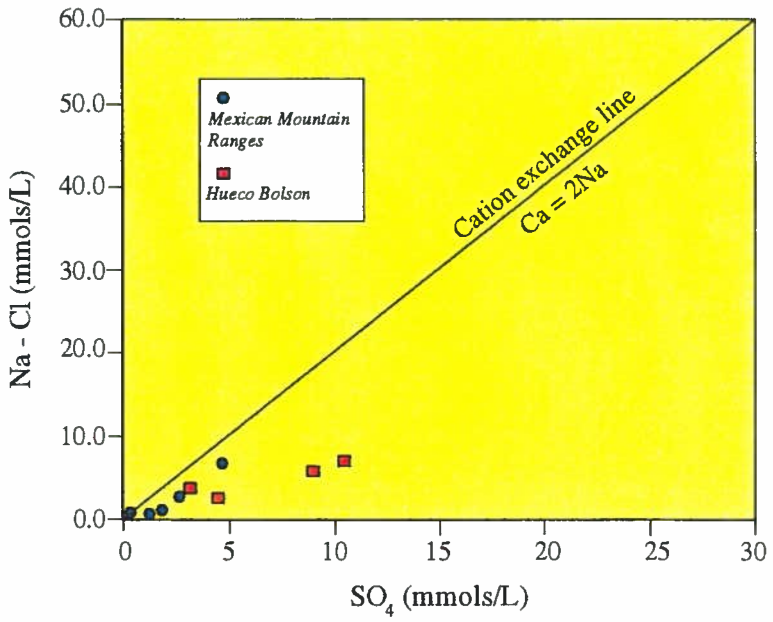

Figure 4.10b. Scatter plot showing (Na - Cl) molar quantity vs molar SO₄ for samples collected from bedrock strata and bolson strata, Mexico (source of data, Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

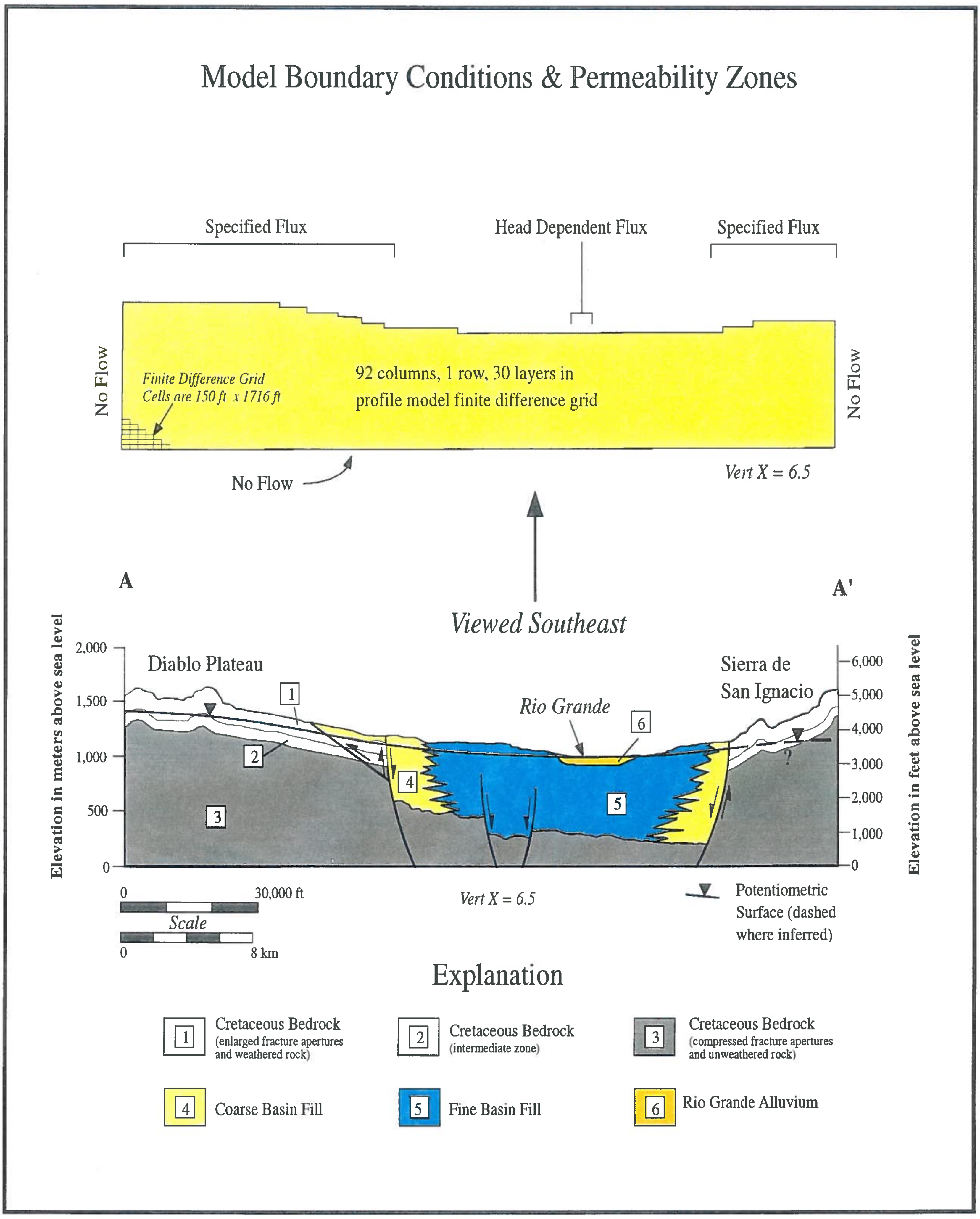

Figure 4.11. Diagram showing the gridding scheme, the aquifer zones, and the boundary conditions selected for the numerical profile model oriented between the Diablo Plateau and the Sierra de San Ignacio (key: zone 1 = Cretaceous rock with enlarged fractures and weathered rock; zone 2 = Cretaceous rock, intermediate zone; zone 3 = Cretaceous rock with compressed fracture apertures and unweathered rock; zone 4 = sand rich basin fill; zone 5 = mud rich basin fill; zone 6 = Rio Grande alluvium).

The northern boundary of the model is no flow, which corresponds to a ground-water divide on the Diablo Plateau. A prescribed flux boundary replenishes the aquifer to the south of the divide. The southern boundary of the model corresponds to an assumed ground-water divide at the Sierra de San Ignacio in northern Mexico. Near the Rio Grande, head-dependent flux boundaries were selected to correspond to low-lying areas near the river where discharge by evapotranspiration and river leakage occurs (Figure 4.11).

Hydraulic conductivities assigned to the model grid were selected from published values (Davis, 1969; Wolff, 1982; Bedinger and others, 1986; Kernodle, 1992; Mullican and Senger, 1992) and from lithologic descriptions of rocks and sediments (Kreitler and others, 1986; Gustavson, 1990; Collins and Raney, 1991). Six permeable rock and sediment zones were specified in the model (Figure 4.11). Zones 1, 2, and 3 were specified in Cretaceous water bearing rocks in the Diablo Plateau and Sierra de San Ignacio (Figure 4.11). These rocks were assigned hydraulic conductivity values of 0.1, 0.03, and 0.007 ft/day (Table 4.2). Cretaceous strata correspond to weathered, slightly fractured carbonate and clastic rocks with expanded fracture apertures (upper zone 1), a intermediate zone (zone 2), and unweathered, slightly fractured carbonate and clastic rocks with compressed fracture apertures (lower zone 3). No evidence of significant karstification of rocks is found in either outcrop or core in the area and flow is fracture and matrix controlled.

The higher permeability pathways near mountain surfaces are assumed to be associated with the tendency of fractures to close with depth due to the increase of mechanical stress (Figure 4.11). Bedinger and others (1986), for example, suggest that hydraulic conductivity is as much as one to three orders of magnitude higher in the upper 100 to 1000 ft of land surface due to weathering, jointing, and expansion of fracture apertures that succeeds erosional unloading of rock overburden. Empirical laws broadly applicable to these permeability trends show the relationship between permeability distribution with depth in fractured rocks (Snow, 1968; Carlsson and Olson, 1977):

$$K(z) = K_s \bullet 10^{-z/l} \qquad (4.1)$$

$$K(z) = K_s \bullet Z^{-1.6} \qquad (4.2)$$

where:

$K(z)$ = hydraulic conductivity as a function of depth

l = a parameter in the range of 100 to 500 m

z = depth in meters beneath land surface (+ downward)

K_s = hydraulic conductivity at land surface

Only small expansion of fracture apertures due to erosional unloading will impart significantly greater permeability to fractured rock units. Shown in simple terms for a parallel plate fracture model (Snow, 1968):

$$K = \frac{W^3}{12\Delta} \qquad (4.3)$$

where:

k = intrinsic permeability

w = uniform fracture aperture width

Δ = uniform spacing between fractures

or for a cubic fracture model (Snow, 1968):

$$K = \frac{W^3}{6\Delta} \qquad (4.4)$$

The cubic relationship between fracture aperture width and permeability shown in (4.3) and (4.4) implies that small compression of fractures due to increasing rock overburden can cause a significant decrease in hydraulic conductivity with depth beneath mountain surfaces, and provides a theoretical basis for this assumption in the numerical model. Ancillary data in the southeastern Hueco aquifer indicate that Cretaceous rocks tested at depths between 600 and 800 ft had lower permeabilities than Cretaceous rocks tested at shallower depths (Mullican and Senger, 1992). Whether this reflects lower permeabilities due to compression of fracture apertures and absence of weathering at greater depth, or a change in lithology, is unknown.

Basin fill deposits that comprise zones 4 and 5 were assigned hydraulic conductivity values of 1.0 and 0.2 ft/day (Figure 4.11; Table 4.2). Higher permeabilities were assigned to the sand rich deposits that flank the highlands and form as alluvial fans (zone 4). Lower permeabilities were assigned to the sandy-silt and clay rich playa and riverine deposits that formed in the Hueco Bolson (zone 5). The Rio Grande alluvium (zone 6), noted for its relatively high permeability, was assigned a hydraulic conductivity value of 10.0 ft/day (Table 4.2). Cenozoic basin fill and Rio Grande alluvium were assigned horizontal to vertical anisotropy ratios of 10:1 (Kernodle, 1992).

Effective porosity values required for ground-water travel time estimates included (Table 4.2): Cretaceous carbonate and clastic rocks (0.08 weathered, 0.05 intermediate, and 0.02 unweathered), sand rich basin fill (0.18), mud rich basin fill (0.25), and Rio Grande alluvium (0.20). These values were compiled from literature values (Wolff, 1982; Bedinger and others, 1986), and from lithologic descriptions of the rocks and sediments (Albritton and Smith, 1965; Kreitler and others, 1986; Gustavson, 1990; Collins and Raney, 1991).

Model results

Model calibration was constrained by using recharge rates of between 0.3 - 3.0% of mean annual precipitation (12 in/yr) as suggested for approximate mountain-front recharge rates in this area by other authors (Kelly and Hearne, 1976; Orr and Risser, 1992). Calibration of the model was achieved by closely matching measured and simulated heads under the additional constraint that travel times estimated by the particle tracking simulator agreed with ground-water residence times estimated by environmental isotopes. Calibrated recharge rates in the Diablo Plateau that averaged 0.14 in/year (1.2% of mean annual precipitation) provided a good match between measured and simulated heads in the American part of the southeastern Hueco aquifer (Figure 4.12). In the Mexican part of the aquifer, published head data are not available beneath the Sierra de San Ignacio and water levels are predicted based on final recharge rates at the Diablo Plateau (Figure 4.12 & 4.13).

Particle tracking results show effects of higher permeability materials on ground-water flow (Figure 4.13 & 4.14). At the Diablo Plateau, particles tend to flow along higher permeability bedrock units specified close to mountain surface, except near the northernmost ground-water divide where vertical hydraulic gradients drive ground water beneath the higher permeability bedrock zones (Figure 4.14). Likewise, these zones do not influence particle trajectories in northern Mexico because of the propensity for vertical flow.

In both the northern and southern portions of the model, the alluvial fans (zone 4) influence particle trajectories and act as sinks for ground-water flow (Figure 4.14). Particles near the lowermost model boundary move vertically upward to the higher permeability alluvial fans in order to follow paths of least hydraulic resistance. The fans act as convergence zones for both short and long flowpaths and thereby function as mixing zones of old and young ground water. Model results are in agreement with environmental isotopes that indicate old ground water at the alluvial fans (established by small percentages of modern carbon) that mix with smaller amounts of young, tritiated ground water (Figure 4.6). Once in the fans, the particles move laterally into lower permeability basin fill and then laterally and vertically upward to low-lying discharge areas near the Rio Grande (Figure 4.14).

Travel times in the model suggest that ground water moving from the models northern boundary may be old (e.g., 20,000 yrs) when it reaches the alluvial fans

Profile Model Parameters, Southeastern Hueco Aquifer

Model zone and rock or sediment unit	Hydraulic conductivity (ft/day)	Effective Porosity	Horizontal to vertical anisotropy ratio
#1: Carbonate and clastic rocks, weathered and expanded fractures	0.1	0.08	1
#2: Carbonate and clastic rocks, intermediate zone	0.03	0.05	1
#3: Carbonate and clastic rocks, unweathered and compressed fractures	0.007	0.02	1
#4: Sand rich basin fill	1.0	0.18	10
#5: Mud rich basin fill	0.2	0.25	10
#6: Rio Grande alluvium	10.0	0.20	10

Table 4.2. Numerical profile model parameters, by zone.

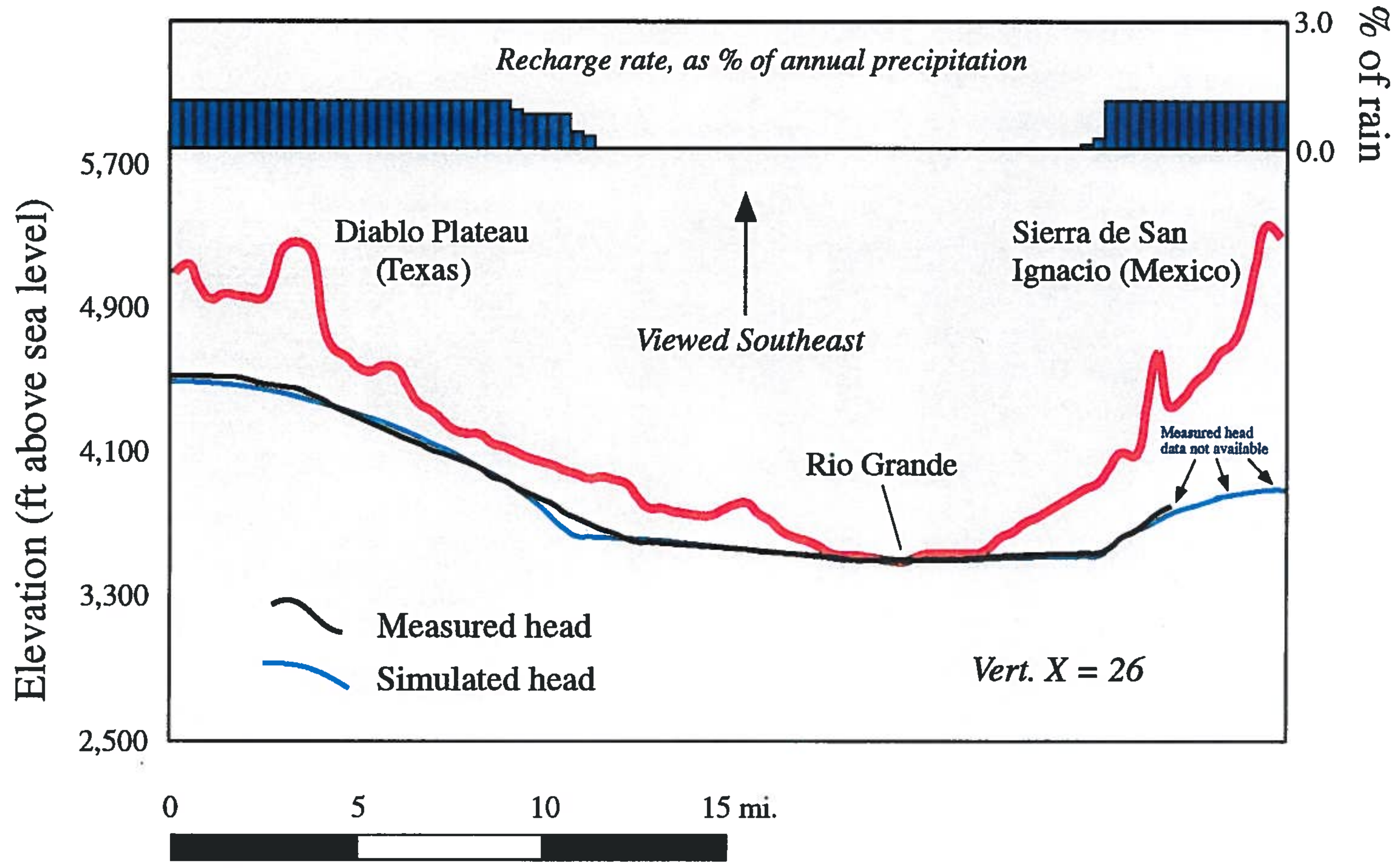

Figure 4.12. Recharge rates and comparison between measured and simulated hydraulic heads in the transboundary profile model.

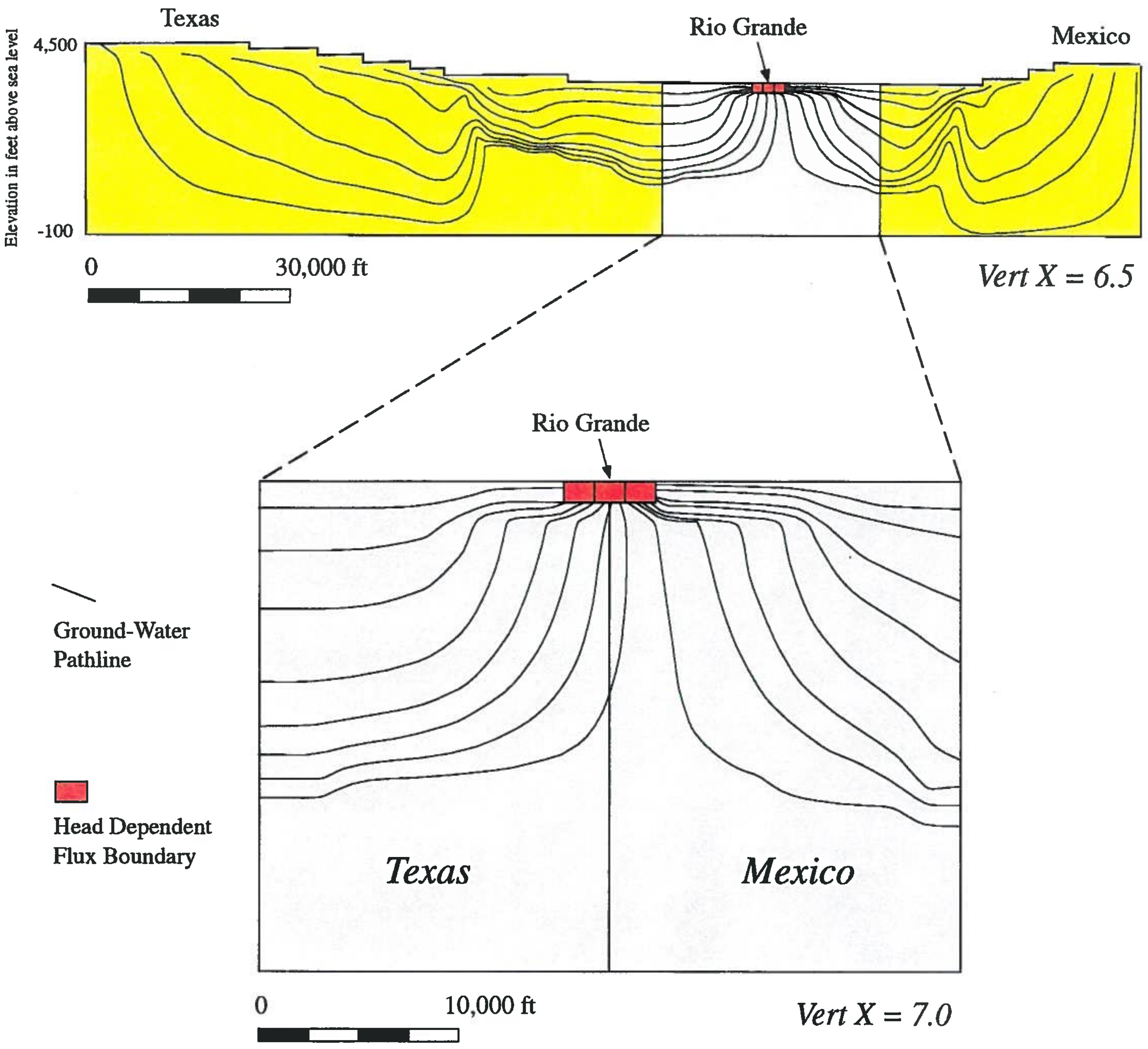

Figure 4.13. Particle trajectories do not form a perfect mirror image where they upwell beneath the international boundary. Pathlines suggest movement of ground water slightly southward into Mexico.

Particle Tracking Results

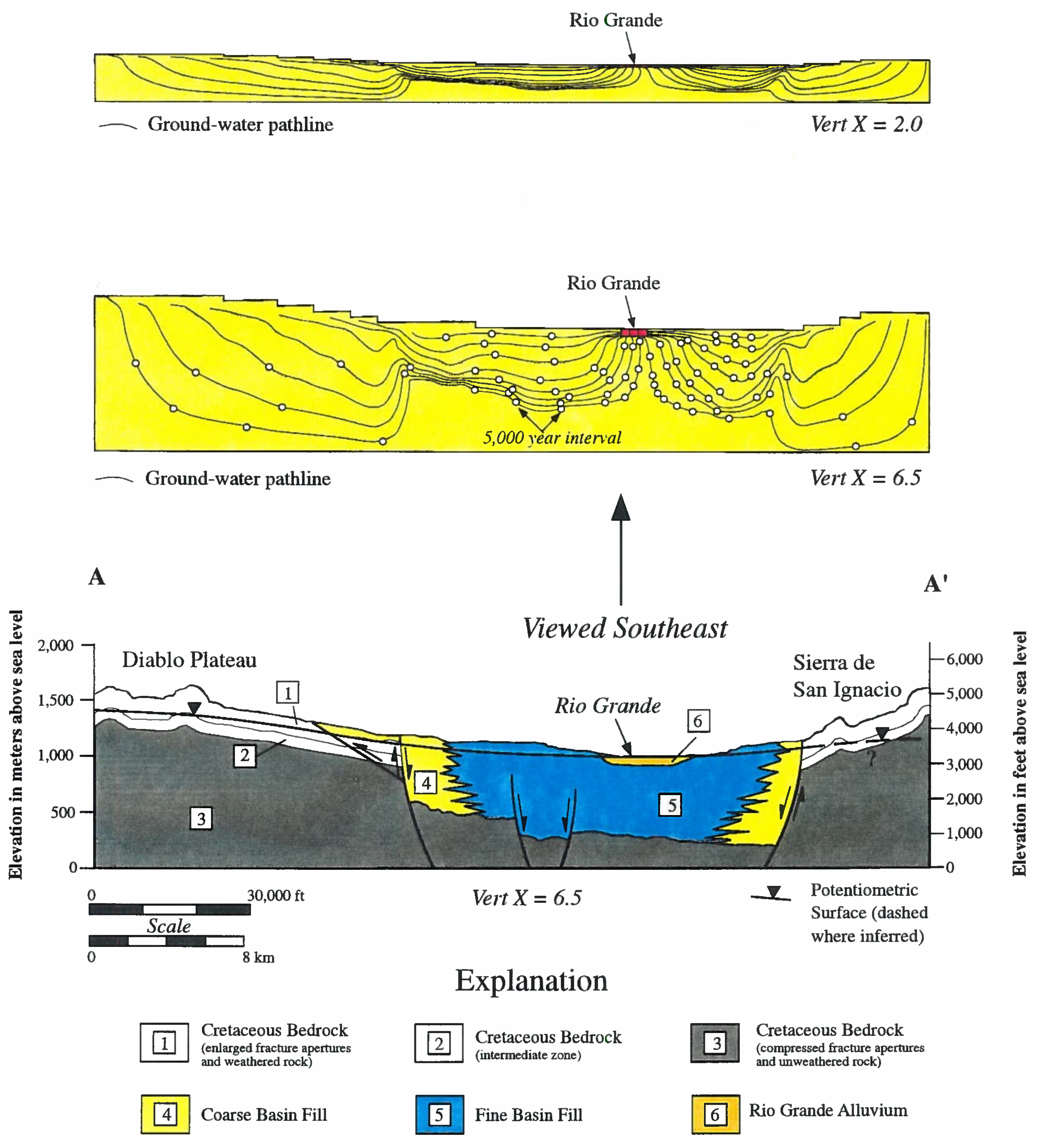

Figure 4.14. Simulated pathlines in the numerical profile model. Alluvial fans act as convergence zones for both short and long pathlines. Pathlines marked by 5,000 year travel times (squares) at segments along the pathline.

(Figure 4.14). Ground water moving from intermediate mountain elevations and from lower mountain elevations varies from moderately-old (1,000 to 8,000 yrs) to very young (100 yrs) when it reaches the alluvial fans. Total estimated travel times from principal recharge areas to the Rio Grande vary from about 15,000 years (alluvial fans Rio Grande) to about 60,000 years (Diablo Plateau ground-water divide Rio Grande).

Particle trajectories do not form a perfect mirror image where they upwell beneath the international boundary (Figure 4.13). Pathlines tend to suggest movement of ground water slightly southward into Mexico before upwelling near the Rio Grande. The asymmetric shape of modeled pathlines is a function of the asymmetric southeastern Hueco Bolson. Predicted movement is not substantially transboundary under simulated steady-state conditions.

Model analyses

Several analyses are performed to assess the response of the model to changes in recharge rates and boundary sinks. Model analyses include:

Scenario 1: Recharge rates in the Sierra de San Ignacio are decreased by a factor of 5.6.

Scenario 2: Heavy aquifer pumping is prescribed north of the Rio Grande.

Scenario 3: Recharge rates are specified to bring mountain flow systems to flow capacity.

Scenario 1

The lack of hydraulic head data in the Sierra de San Ignacio did not allow us to match measured and simulated heads in Mexico. Recharge rates were assumed equal in the Diablo Plateau and Sierra de San Ignacio. Flat lying surfaces in the Diablo Plateau may be more effective recharge areas than the steep terrains in the Sierra de San Ignacio (Figure 4.12). The steeper mountain surfaces in Mexico may reduce infiltration rates and favor surface runoff.

To test the effect of lower recharge rates in Mexico due to topographic influences, the recharge rates in the Sierra de San Ignacio are decreased to 0.025 in/year (0.21% of mean annual precipitation) from an initial recharge rate of 0.14 in/year (Figure 4.15). The lower recharge rate is selected arbitrarily to assess effects on pathlines and transboundary ground-water flow. Recharge rates in the Diablo Plateau remain unchanged (Figure 4.15).

Movement of ground water from the United States into Mexico is more pronounced in the analysis (compare Figures 4.13 and 4.16). Ground water moves nearly 3,200 ft into Mexico, or about 2,000 ft more than in the initial model run. The Rio Grande alluvium acts to refract pathlines in Mexico and creates a more imperfect pathline image on both sides of the international border.

Scenario 2

Movement of ground water across the international border to pumping cones of depression is tested. A number of wells are placed in basin fill, 15,400 ft north of the Rio Grande. Water wells are pumped at a steady rate.

Drawdown cones of depression caused by well pumping are sufficient to lower heads in the southeastern Hueco Bolson and induce infiltration from the Rio Grande (Figure 4.17). Drawdown cones do not cause hydraulic head detachment from the river. Pathlines originating at higher elevations in the Sierra de San Ignacio move across the international border to the pumping cones of depression (Figure 4.18). Pathlines that originate at lower elevations in Mexico move to discharge areas near the Rio Grande.

Radial flow patterns are implicitly ignored in a two-dimensional profile model. The physics of drawdown in the profile model do not replicate precisely the physical drawdown configurations that accompany well pumping. Profile models are sometimes used even when pumping wells are oriented along the line of profile (Sanford and Konikow, 1985). Even so, results must be scrutinized as limited. Constraints are that pathlines move across the international boundary to areas where hydraulic head is below river stage, expected in areas where pumping causes substantial drawdown.

Scenario 3

Flow capacity is defined as the maximum amount of water that a flow system can accept and transmit. The phrase “rejected recharge” typically is applied to an aquifer at flow capacity where precipitation infiltration or other sources of potential recharge exceed the capacity of the saturated zone to accept additional recharge (Figure 4.19). Usually this results in regional saturation of the water table at land surface. The characteristics of a flow system that influence flow capacity are slope of the terrain and permeability of the aquifer (Mifflin, 1968).

Moisture is not available for flow capacity to be attained in most arid aquifers. Climatological change as a result of global warming or cooling may cause an arid system to later reach flow capacity. Abandoned landfills and dumps may become inundated, creating a potentially threatening water quality problem.

Paleohydrologic evidence of flow capacity in arid aquifers is observed in the southwestern Basin and Range province (Mifflin, 1968). Flow capacity was established in some of these aquifer during the Pluvial periods of the late Pleistocene Epoch, when precipitation was higher. Recent concerns about global warming intensify concerns about possible effects on groundwater quality. The southeastern Hueco aquifer, like most desert aquifer, is not at flow capacity today.

Recharge rates needed to attain flow capacity in the southeastern Hueco aquifer highlands are predicted by placing a series of drains at land surface elevation, and by increasing recharge rates until flow capacity is attained (head is at land surface and springs are omnipresent). Specified flux is prescribed so that the recharge rates exceed the terrain’s capacity to take the prescribed recharge, and potential recharge is rejected. Drains along the mountain surfaces act as conduits for rejected recharge (Figure 4.20).

Recharge rates needed to attain flow capacity are about 0.41 in/year (3.4% of mean annual precipitation) along the Diablo Plateau and 1.49 in/year (12.4% of mean annual precipitation) along the Sierra de San Ignacio (Figure 4.21). These recharge rates are 293% and 1064% higher than initial calibration recharge. Results imply that a moderate increase in the recharge rates at the Diablo Plateau might be sufficient to bring the Diablo Plateau to flow capacity. The substantial increase in the recharge rate required to bring the Sierra de San Ignacio to flow capacity is probably not realistic and suggests that this system will not attain flow capacity in Mexico.

Model limitations

The paucity of data along the model profile limits the use of the model beyond that of an interpretive tool for estimating ground-water flowpaths and velocities. The model presents a simplified picture of the hydrostratigraphy of the area, as defined by major structural and geologic features such as the southeastern Hueco Bolson. The simulated hydraulic gradient was suitably matched with the actual hydraulic gradient where head data were available, but the model’s reliability is limited by the lack of information on vertical and horizontal hydraulic conductivity, effective porosity, and hydrostratigraphy. The limiting factors that are most pertinent to this modeling effort include the assumptions that:

- Fractured rock, at large scales, is equivalent to a porous medium.
- Ground-water flow is restricted to the plane of the profile model.

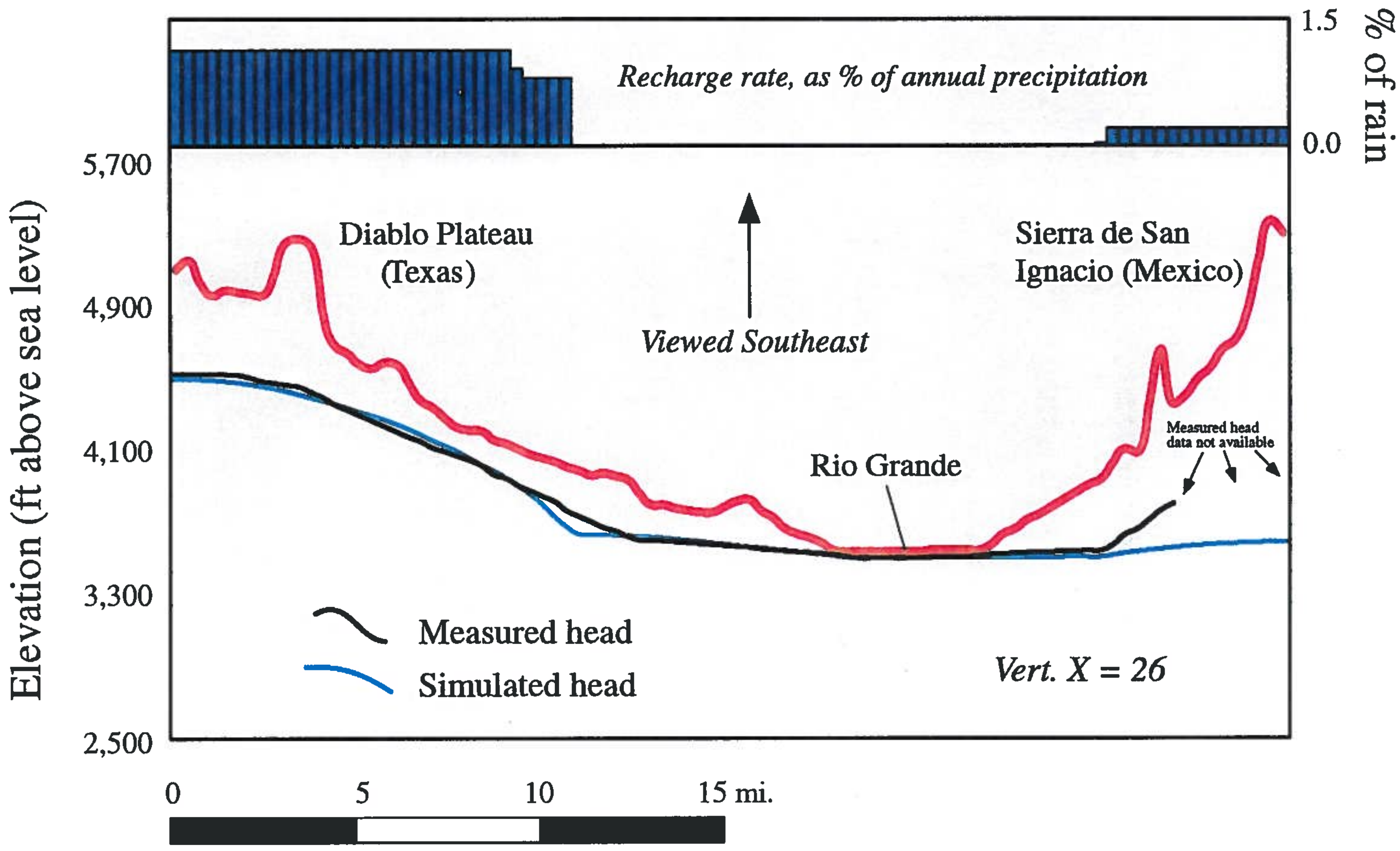

Figure 4.15. Recharge rates and comparison between measured and simulated hydraulic heads in model scenario 1. Prescribed recharge rates are much higher in the United States.

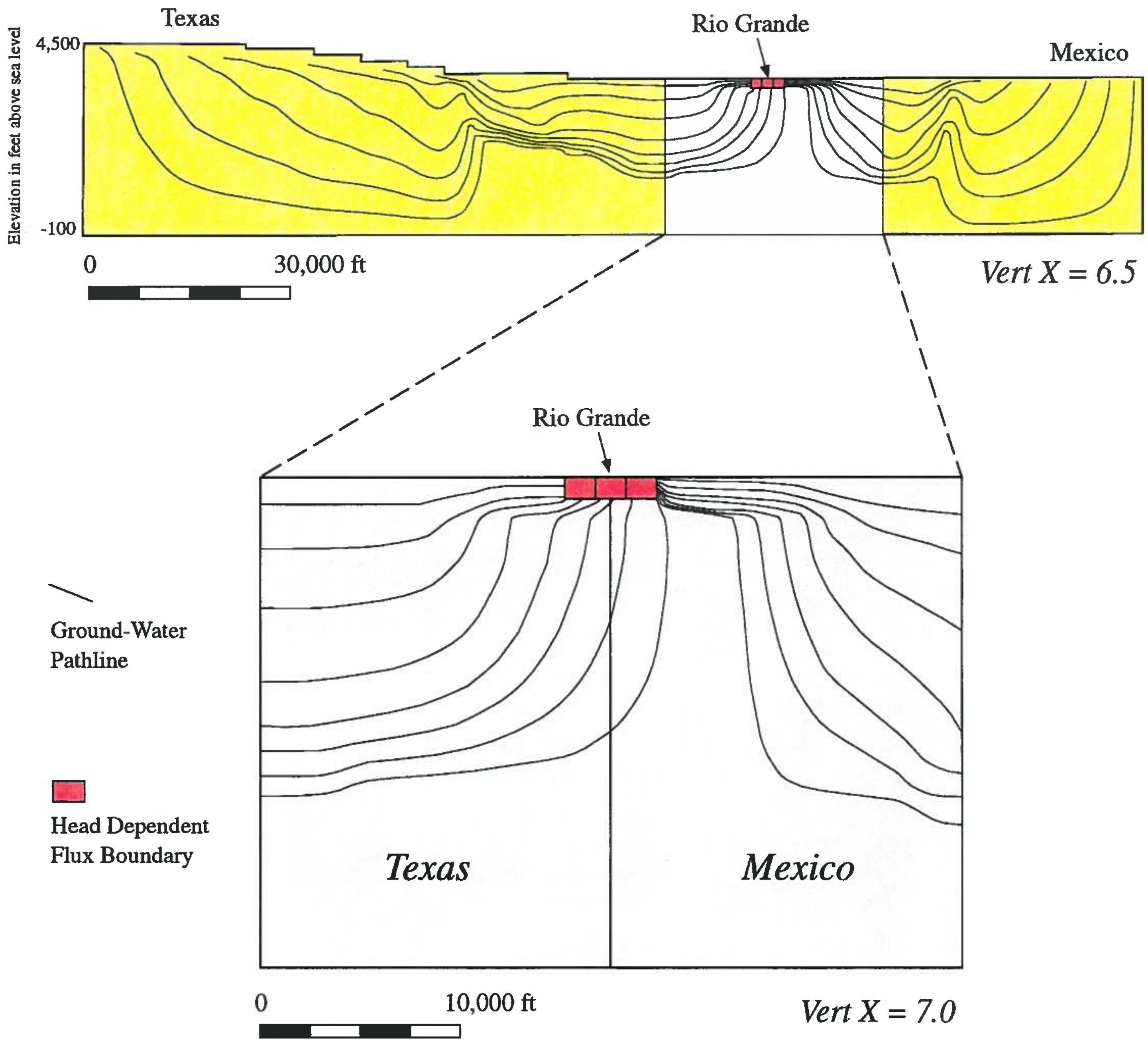

Figure 4.16. Pathlines suggest greater movement of ground water into Mexico with lower recharge rates in the Sierra de San Ignacio, model scenario 1.

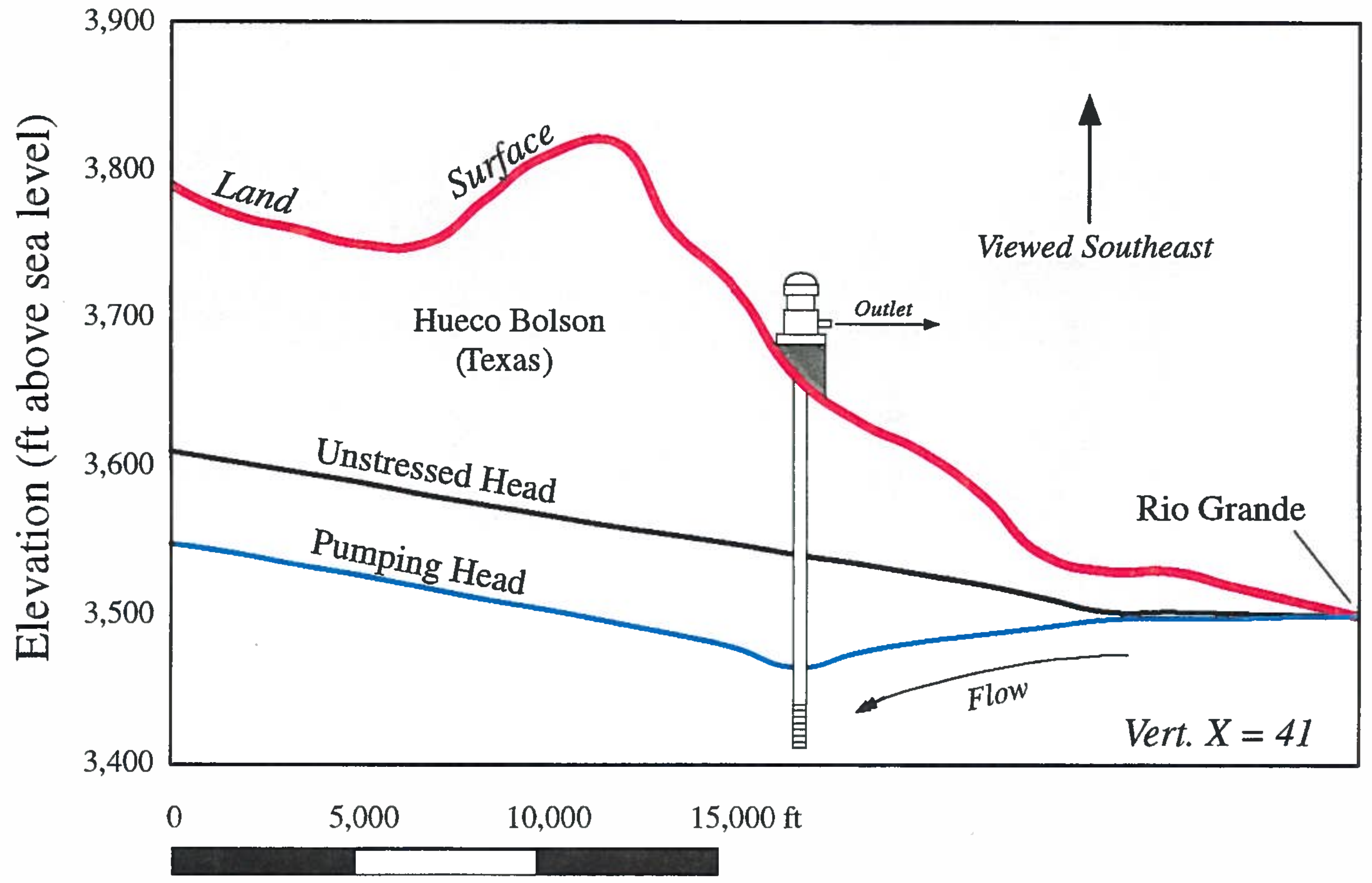

Figure 4.17. Comparison of unstressed hydraulic head and pumping hydraulic head in the numerical profile model, model scenario 2. Pumping cones of depression lower hydraulic head in the Hueco Bolson and induce infiltration of surface water from the Rio Grande.

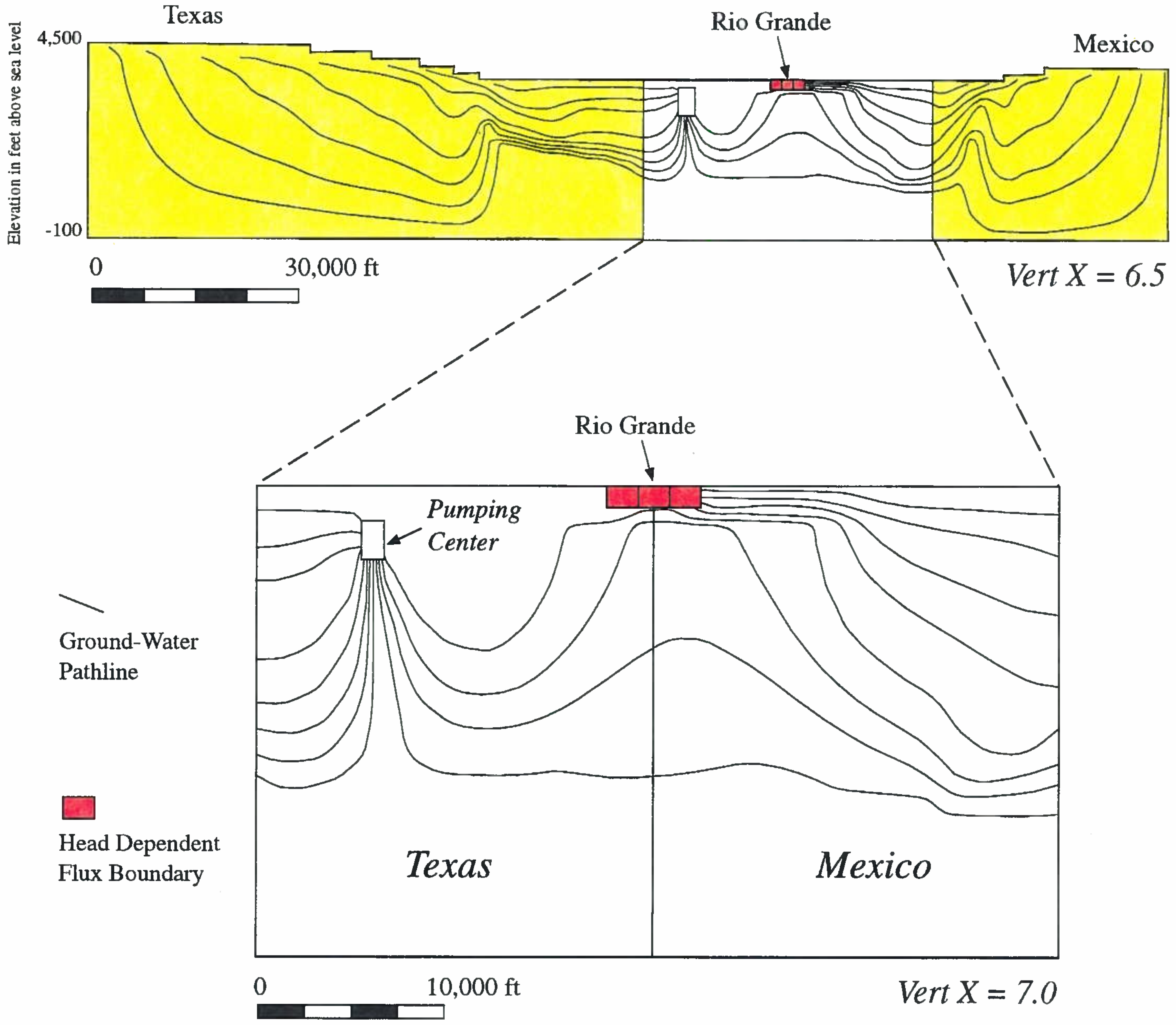

Figure 4.18. Pathlines originating in Mexico move across the international border to pumping cones of depression in the Texas portion of the southeastern Hueco Bolson in model scenario 2.

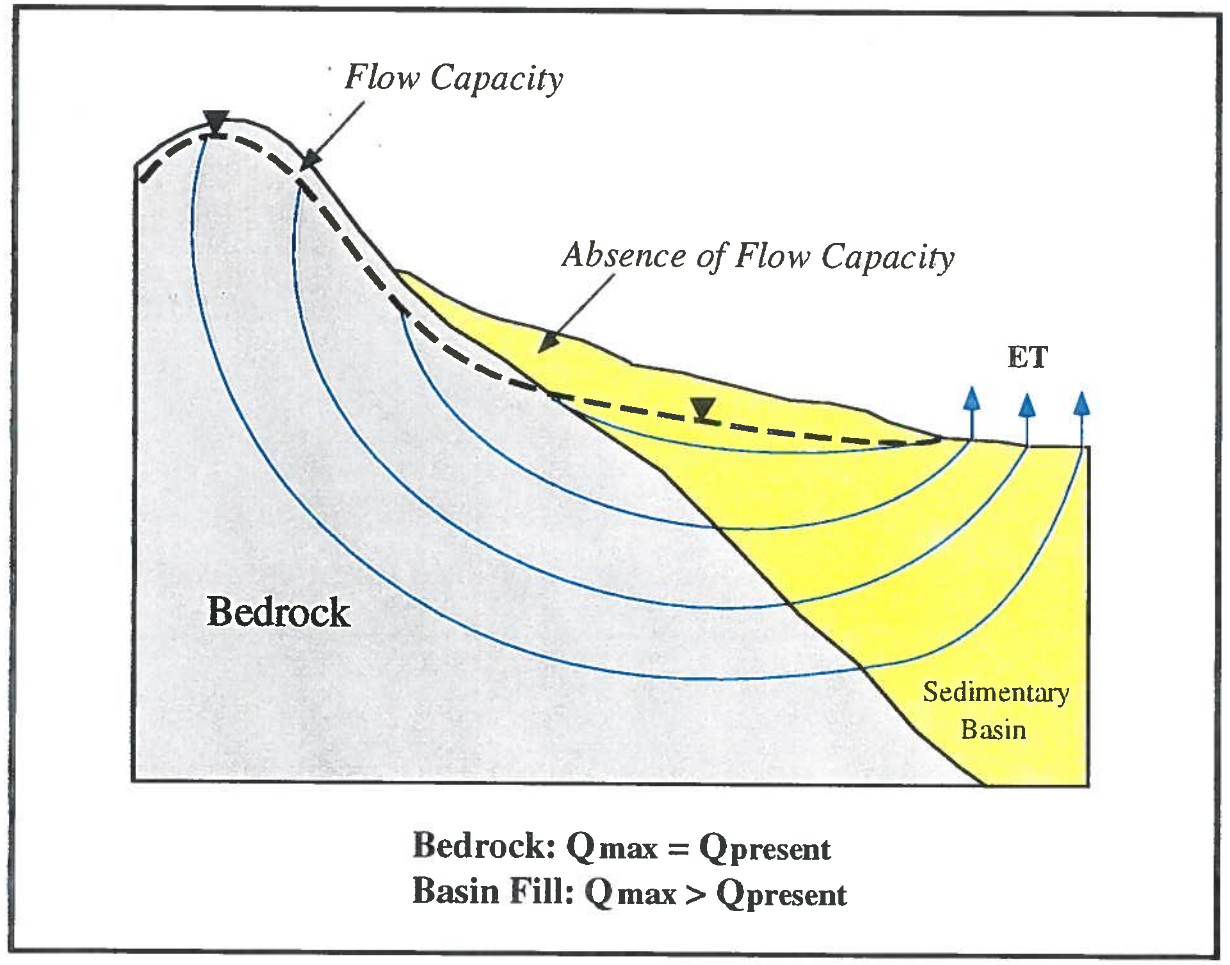

Figure 4.19a. Diagram showing flow capacity in the highland bedrock aquifer and absence of flow capacity in the sedimentary basin aquifer (modified from Mifflin, 1968).

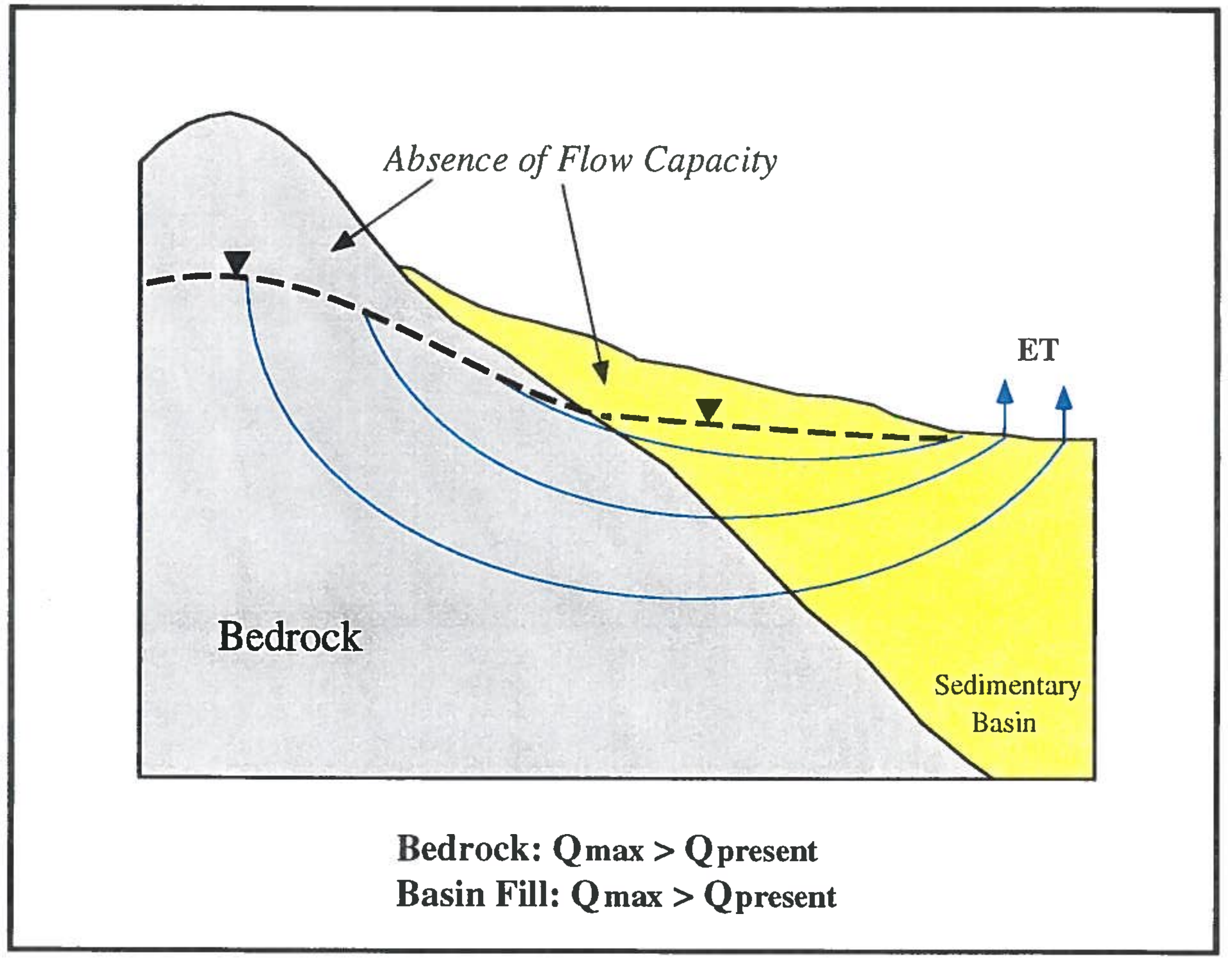

Figure 4.19b. Diagram showing absence of flow capacity in the bedrock and basin aquifers. Mountains in desert basins are typically not at flow capacity (modified from Mifflin, 1968).

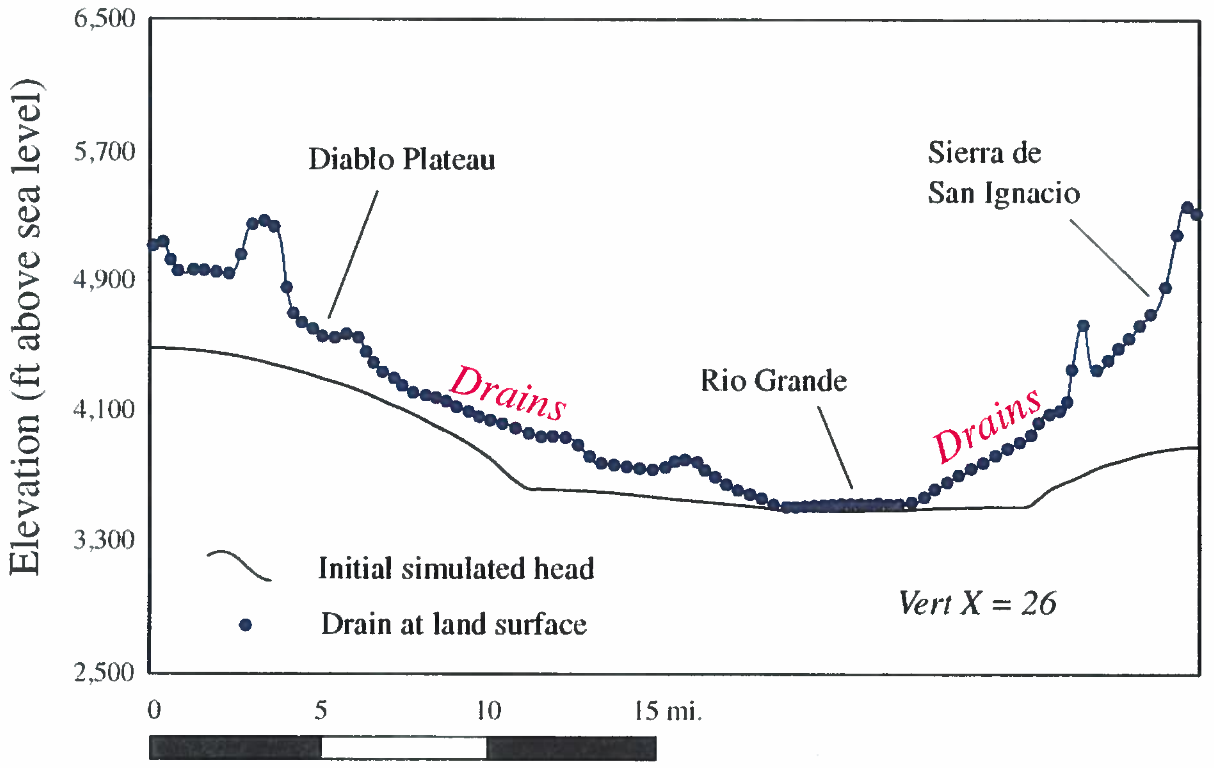

Figure 4.20. Drains specified at land surface elevation in the numerical profile model, model scenario 3.

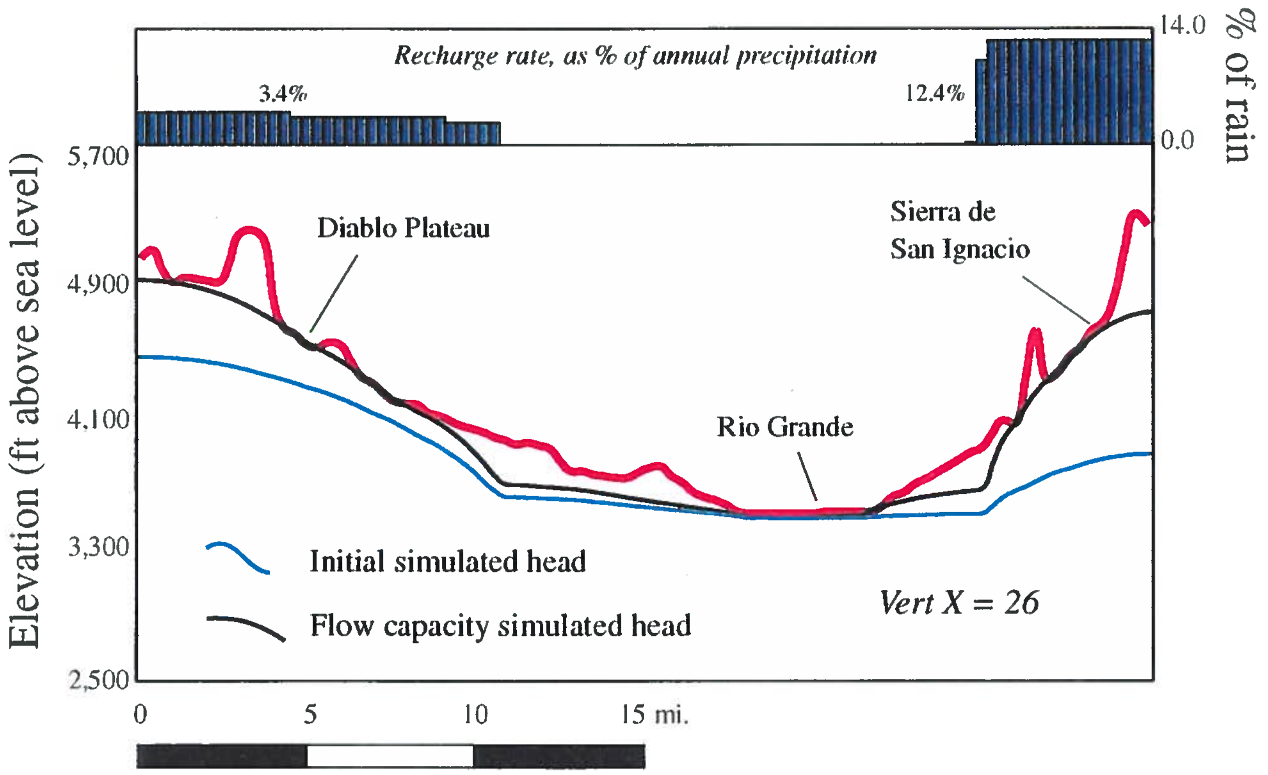

Figure 4.21. Comparison of initial simulated hydraulic head (see Figure 4.12) and simulated hydraulic head at flow capacity; and recharge rates at flow capacity, model scenario 3.

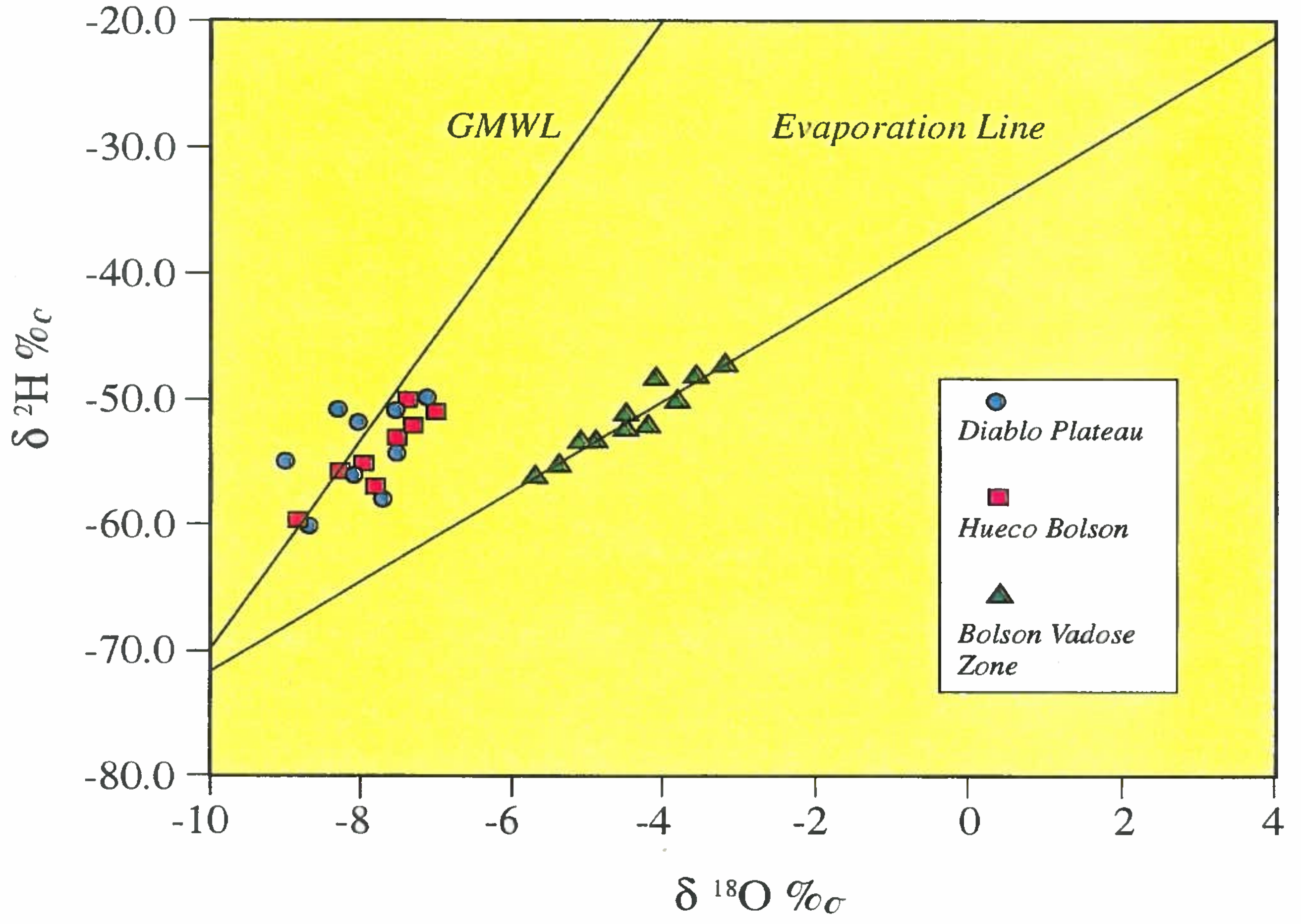

Figure 4.22. Binary plot of δ^2H versus δ^{18}O values for vadose zone and saturated zone waters in the southeastern Hueco aquifer. Stable hydrogen and oxygen isotope ratios in ground water (Diablo Plateau and Hueco Bolson) plot generally along the global meteoric water line (GMWL), indicating little or no enrichment associated with evaporation. Stable isotope ratios in vadose zone waters fall along an evaporation line. The lower slope is attributed to enrichment from the substantial excess of evaporation over precipitation. At distances from arroyos that act as sites of focused recharge, results imply no precipitation recharge along the basin floor due to high evaporation rates (source of data, Fisher and Mullican, 1990; Bureau Of Economic Geology, unpublished field data).

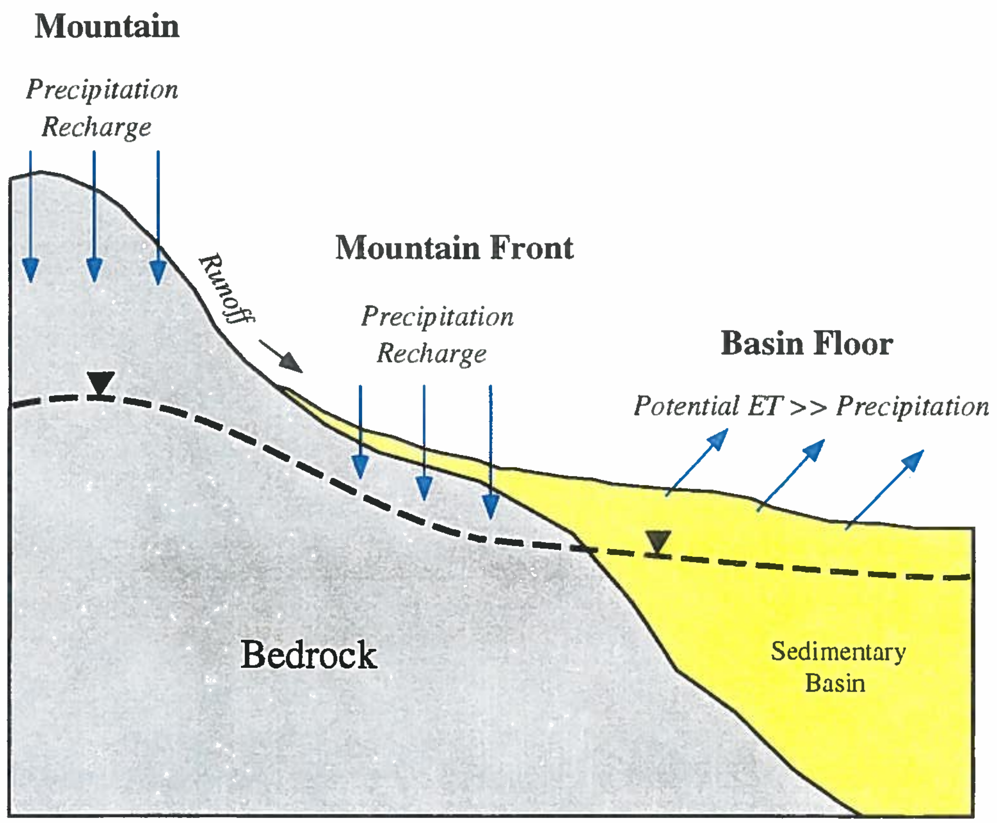

Figure 4.23. Conceptual model showing mountain and mountain front recharge and the absence of precipitation recharge along the basin floor due to the substantial excess of evapotranspiration over precipitation.

- Recharge rates at the Sierra de San Ignacio are approximately equal to recharge rates at the Diablo Plateau.

- Each of the zones has a constant vertical and horizontal hydraulic conductivity and effective porosity.

Of these, the most limiting is the last assumption. It is certain that rock units in any particular zone are laterally and vertically heterogeneous. These zones were defined by the boundaries between rock and sediment types. Within Cretaceous rocks for example, structural attributes and transitions in the potentiometric surface were used to separate the water-bearing units into zones. The simplistic definition of zones that have uniform hydrogeologic properties is required because borehole and aquifer test data are not available at most depths simulated in the model. Nevertheless, the model provides useful insights on pathlines, residence times, and potential transboundary movement of ground water in the asymmetric southeastern Hueco aquifer.

Susceptibility to Contamination

Bedrock units exposed in the southeastern Hueco aquifer are moderately susceptible to contamination. The Diablo Plateau has a moderate ground-water pollution potential (DRASTIC index) that ranges from 95 - 124 for agricultural sources (TWC, 1989). The DRASTIC index for general, municipal, and industrial sources is lower, ranging from 65 - 94 (TWC, 1989).

The bolson has a higher DRASTIC index, ranging from 110 - 124 for agricultural sources and from 80 - 94 for general, municipal, and industrial sources (TWC, 1989). Some qualification of this ranking is required. Even though the potential for contaminants at land surface being carried with infiltrating precipitation to the saturated zone is possible along arroyos (established by radioisotopes, Figure 4.6), the potential for contamination along areas of the basin floor that are not juxtaposed to arroyos is generally small. The relatively dry climate, specific retention of the soil, and intensity and distribution of rainfall does not provide adequate moisture for wetting fronts to reach the saturated zone except along arroyos.

Evidence of the lack of precipitation recharge through soil profiles beneath the basin floor is provided by a comparison of stable isotopes for ground waters in the Diablo Plateau'and Hueco Bolson with soil water extracted from the unsaturated (vadose) zone in the bolson (Figure 4.22). Stable isotopes in ground water typically plot along the global meteoric water line (GMWL) of Craig (1961), whereas the waters extracted from the vadose zone plot along an evaporation trend. The vadose zone waters are enriched with respect to the heavier stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) due to the substantial evaporation of lighter water molecules (i.e., those that contain $\delta^{16}O$ and $\delta^{1}H$) from soil profiles (Figure 4.23). Having a slightly different vapor pressure, the forms of water molecules that contain the lighter isotopes tend to evaporate preferentially leaving behind a solution enriched with respect to heavier water molecules. This process is known as fractionation.

Results show a clearly defined stable isotope signature for ground waters in the southeastern Hueco aquifer that is genetically different from the stable isotope signature of water extracted from the vadose zone. The data indicate that ground waters are meteoric and undergo little isotopic fractionation by evaporation (Figure 4.23). Ground water is probably recharged rapidly in limited quantities after episodic precipitation and runoff events that provide sufficient moisture for ephemeral saturation of pediments and arroyos that overlie and flank the mountains.

Limited contamination potential may not be a valid assumption where anthropogenic structures are in place. Quarry's, excavations, and abandoned and poorly constructed water wells all can serve as conduits for contamination from land surface.

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CHAPTER 5 - RIO GRANDE AQUIFER

Location and Extent

Near the southeastern limit of the Mesilla Valley, the Rio Grande is constricted between the Sierra de Cristo Rey and the Franklin Mountains in a canyon known as the "El Paso narrows." Here the canyon is about 1,500 ft 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, the "El Paso Valley" that has incised the surface of the Hueco Bolson (Figures 1.2 and 5.1). Near El Paso, the El Paso Valley is about 6 to 8 miles wide and is a little more than 200 ft deep (USBR, 1973). The valley trends nearly 90 miles east, southeast to Fort Quitman where the valley again is constricted in a valley between the Sierra de la Cieneguilla and the Quitman Mountains. The valley deepens along its southeasterly trend and is almost 330 ft deep near Fabens, 30 miles below El Paso. The valley wall is disrupted frequently by arroyos that incise the Hueco Bolson and floodplain surfaces.

Stratigraphy and Water-Bearing Characteristics

Sediment types

The Rio Grande alluvial floodplain in the Mesilla and El Paso Valleys 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 (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 Mesilla and El Paso Valleys. Total thickness of the Rio Grande alluvium is reported to average about 210 ft in the United States (IBWC, 1989). Average thickness is about 170 ft in Mexico (IBWC, 1989). Saturated alluvium thicknesses average 188 and 148 ft respectively in the American and Mexican portions of the floodplain, El Paso 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 15 ft thick (IBWC, 1989). Windblown deposits are surfaces for infiltration and recharge because they are well sorted and sparsely vegetated.

Aquifer properties

Aquifer tests are not available for the Rio Grande aquifer in the El Paso Valley. Lee Wilson and Associates (1986) report that hydraulic conductivity values probably vary from 20 to 250 ft/day. Calibration of a three-dimensional finite difference model provided bulk hydraulic conductivity values of 65 ft/day (Lee Wilson and Associates, 1986). In an earlier model, Meyer (1976) derived average transmissivity values for the Rio Grande alluvium of about 4,000 ft^2/day. The hydraulic conductivity value is about 21 ft/day in Meyer's model. Specific yield for the unconfined aquifer probably ranges from 0.15 to 0.35 ft/day (Lee Wilson and Associates, 1986). Coarser deposits trend toward lower values and fine textured deposits trend toward higher values. Most of the principal water bearing strata have specific yields that range from about 0.15 to 0.20 (Alvarez and Buckner, 1980; IBWC, 1989)

Potentiometric Surface Maps and Water Levels

Water level contour maps prepared with data collected in 1973 - 74 (Figure 5.2) and 1994 - 1995 (Figure 5.3) illustrate losing stream, underflow, and baseflow conditions on different segments of the alluvial floodplain (Figure 5.4). The condition of losing stream is apparent along the Chamizal zone (Figure 5.1) where drawdown cones from municipal well fields have reversed the hydraulic gradient between the river and the Rio Grande aquifer. Drawdowns have intensified along the Chamizal zone since 1973. Alluvial underflow (Figure 5.4) predominates between the Chamizal zone and the El Paso/Hudspeth county line. Along this stretch of floodplain, ground-water flows subparallel to the direction of surface discharge, and head in the aquifer is approximately equal to the head in the river. The head elevation along this reach did not change significantly since 1973 (Figures 5.2 and 5.3).

The condition of baseflow prevails between county line and Fort Quitman (Figure 5.4). Flow is oriented subperpendicular to the direction of surface discharge and ground water clearly discharges to the Rio Grande. Hydraulic head in this part of the floodplain has increased since 1973 (Figures 5.2 and 5.3).

Hydrographs prepared with data collected from 1970 to 1995 illustrate annual water-level fluctuations and explain temporal changes in the potentiometric surface maps (Figures 5.5 and 5.6). Increasing and decreasing water-level elevations correspond to areas where ground water is added or depleted from the aquifer. Depletion of storage has occurred along and several miles below the Chamizal zone (Figure 5.1) due to (1) grout lining of the Rio Grande channel and (2) heavy pumping in the Hueco-Tularosa aquifer (Figure 5.5). Lining of the channel intensified drawdowns because of hydraulic detachment of the water table from the river (i.e., an unsaturated zone now exists between the stream bed and the water table). Depletion of storage in the Hueco Bolson is partially replenished by leakage from the Rio Grande aquifer at the expense of its own storage. Limited surface irrigation combined with extensive paved surfaces along this heavily urbanized reach allow little recharge from the surface and exacerbates depletion of the Rio Grande aquifer.

Between the Chamizal zone and the El Paso/Hudspeth county line, most hydrographs indicate small annual fluctuation, but generally no appreciable net change in storage (Figures 5.1 and 5.5). The large number of drain laterals along this heavily irrigated area help to maintain nearly constant water-levels. Drains tap the bank storage in the alluvial aquifer.

Between county line and Fort Quitman, several hydrographs indicate net addition of water to storage (Figures 5.1 and 5.6). Excessive surface water applied to the floodplain has added additional storage to the shallow water table aquifer. Drains along this segment of the floodplain apparently are not present in sufficient density to maintain constant ground-water levels.

Many of the hydrographs illustrate notable drawdowns in 1977 and 1978 (Figures 5.5 and 5.6). Irrigation pumping in the El Paso Valley totaled 88,260 and 92,850 acre-feet in 1977 and 1978 (IBWC, 1989). The pumpage rate averaged only 43,360 acre-ft/year between 1950 and 1984 (IBWC,1989). Heavy pumping and temporary drawdown in 1977 and 1978 were a result of drought conditions and reduced surface flows.

Ground-Water Availability

Surface area of alluvial floodplain between the El Paso narrows and Fort Quitman (Figure 5.1) is about 152 mi^2 in the United States and about 123 mi^2 in Mexico. Average saturated thicknesses are about 188 ft in the United States and about 148 ft in Mexico (IBWC, 1989). Using these figures and a specific yield of 0.2, the total volume of water in the Rio Grande aquifer in the study area is an estimated 5.99 million acre-ft (3.66 million acre-ft in the United States and 2.33 million acre-ft in Mexico). Values are approximate due to uncertainty in estimates of alluvial thickness and spatial variability of specific yield. Volumes of

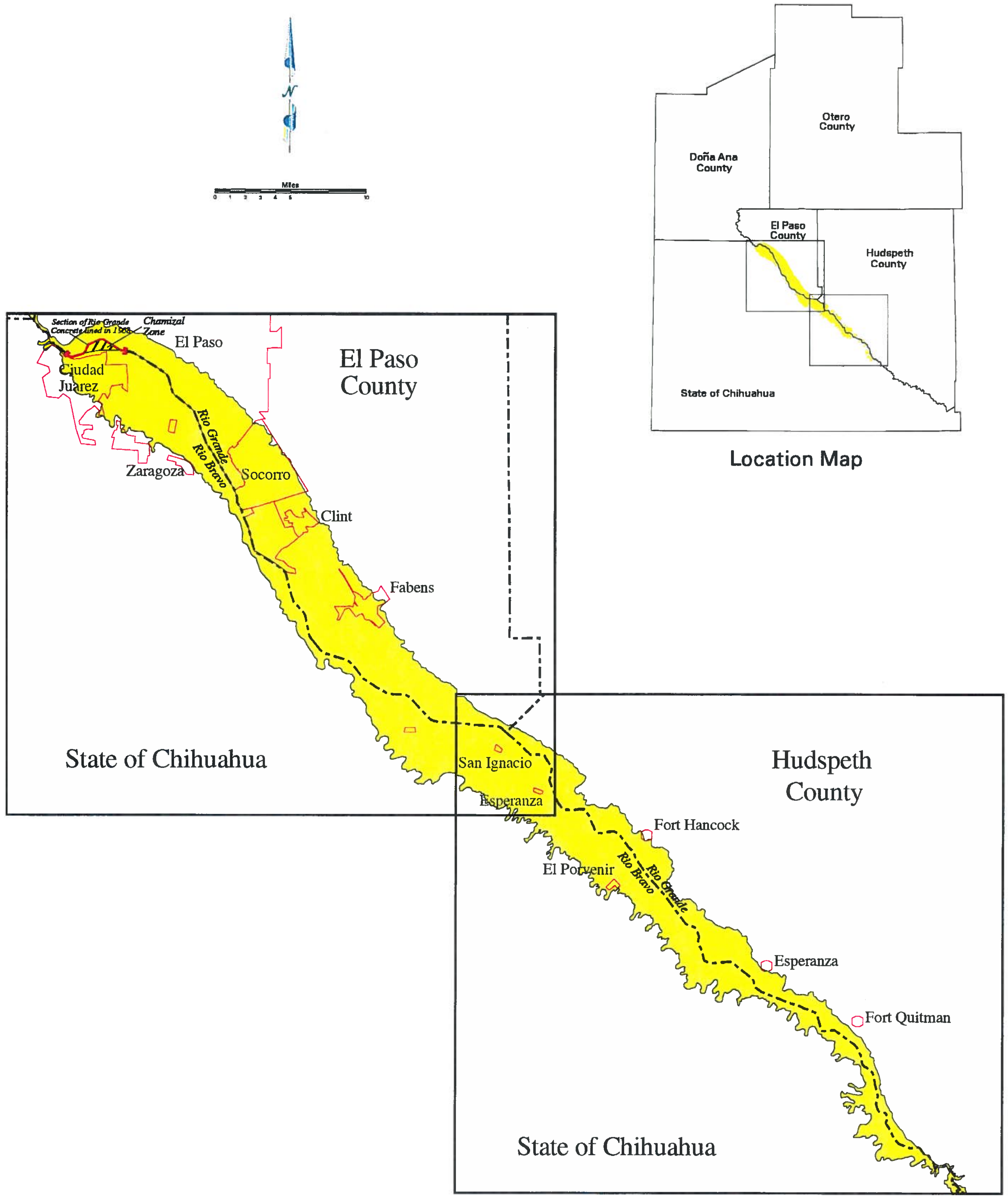

Figure 5.1. Location of the Rio Grande aquifer in the study area

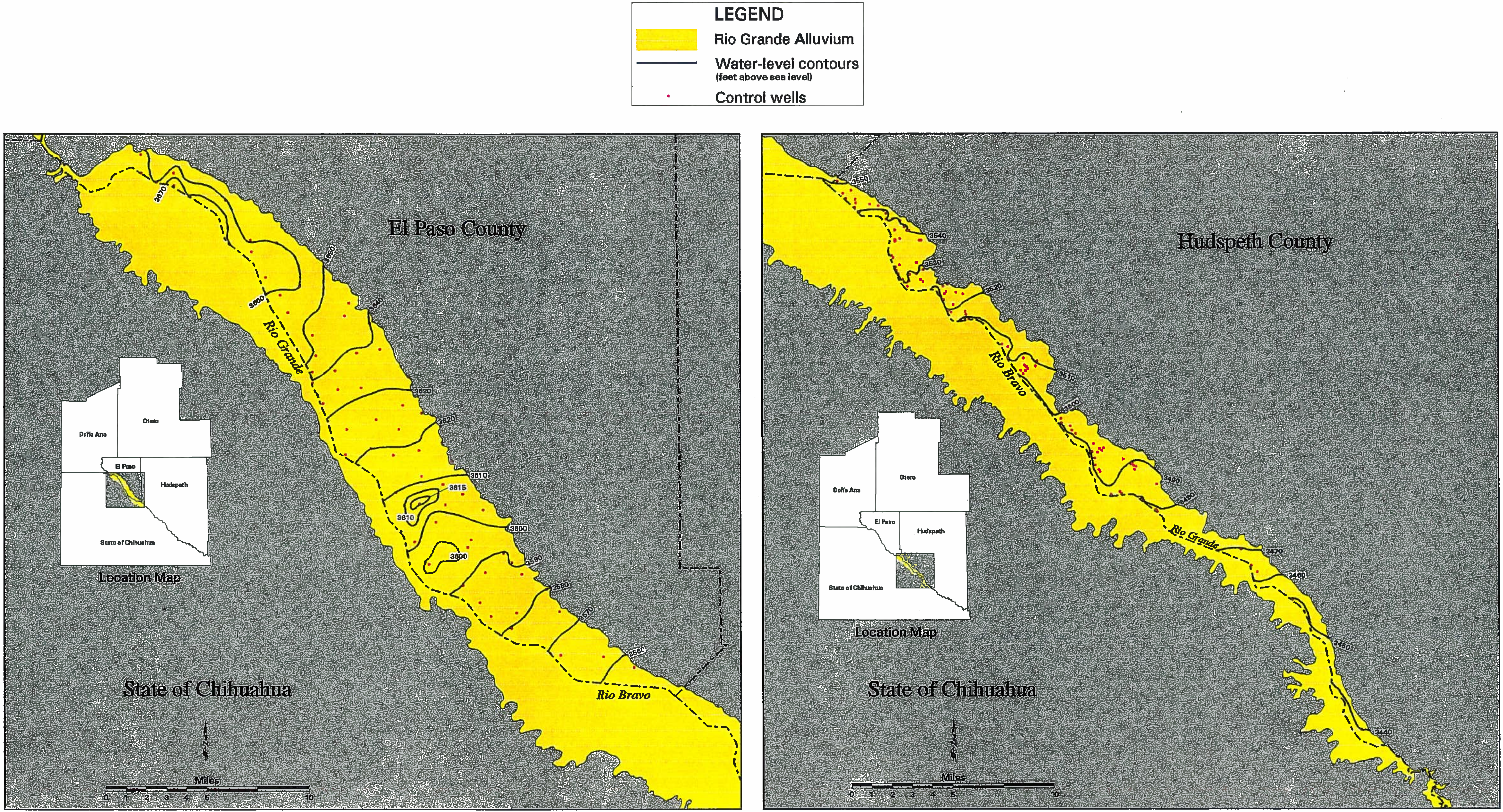

Figure 5.2. Water level contour map for the Rio Grande aquifer in El Paso and Hudspeth Counties, 1973 and 1974. Map illustrates losing stream, underflow, and baseflow conditions at different segments of the floodplain (source of data, Texas Water Development Board).

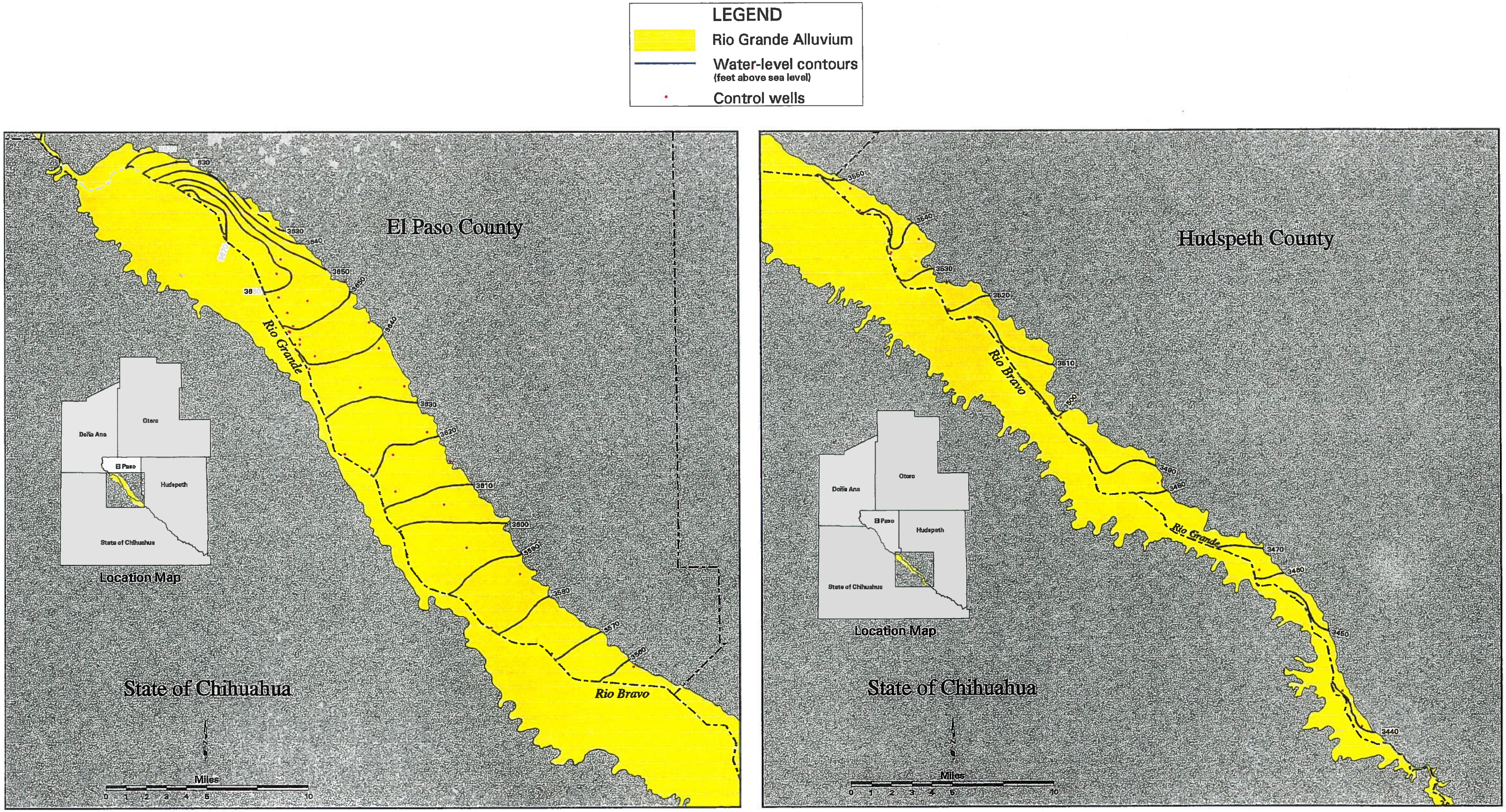

Figure 5.3. Water level contour map for the Rio Grande aquifer in El Paso and Hudspeth Counties, 1994 and 1995. A comparison of figures 5.2 and 5.3 indicates that drawdowns have intensified in the El Paso area since 1973 (see figure 5.1 for delineation of the El Paso area. Source of data, Texas Water Development Board).

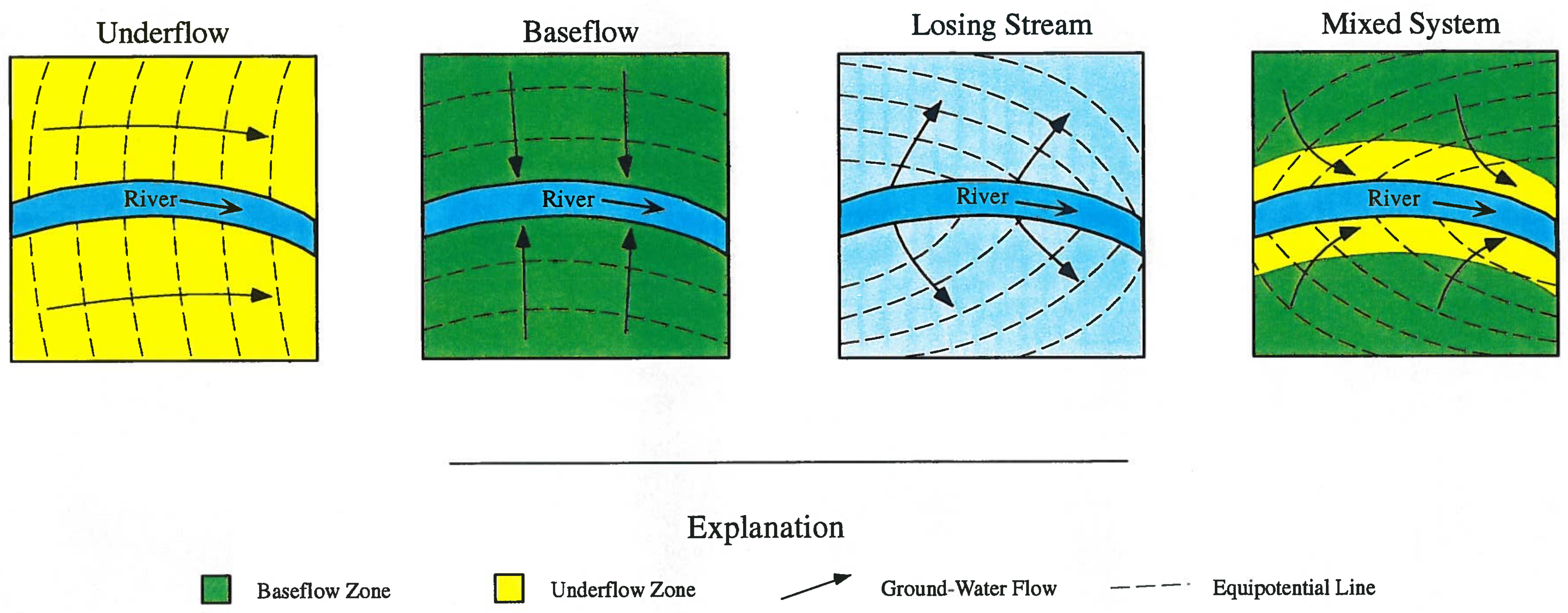

Figure 5.4. Diagram illustrating underflow, baseflow, losing stream, and a mixed system that includes underflow and baseflow components of flow in an alluvial aquifer hydraulically connected to a river (modified from Larkin, 1988).

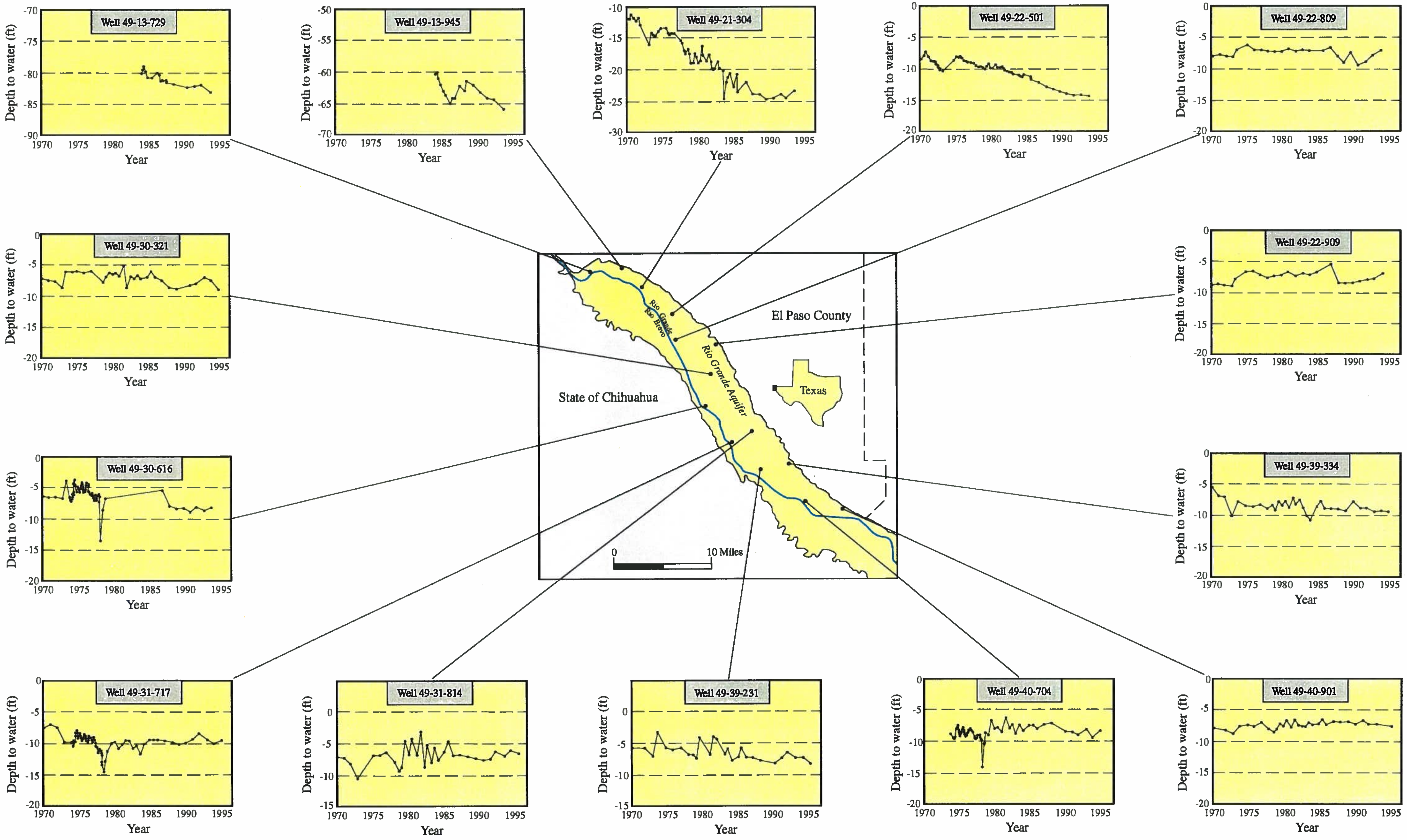

Figure 5.5. Hydrographs illustrating water-level changes in the Rio Grande aquifer in El Paso County between 1970 and 1995 (source of data; Texas Water Development Board).

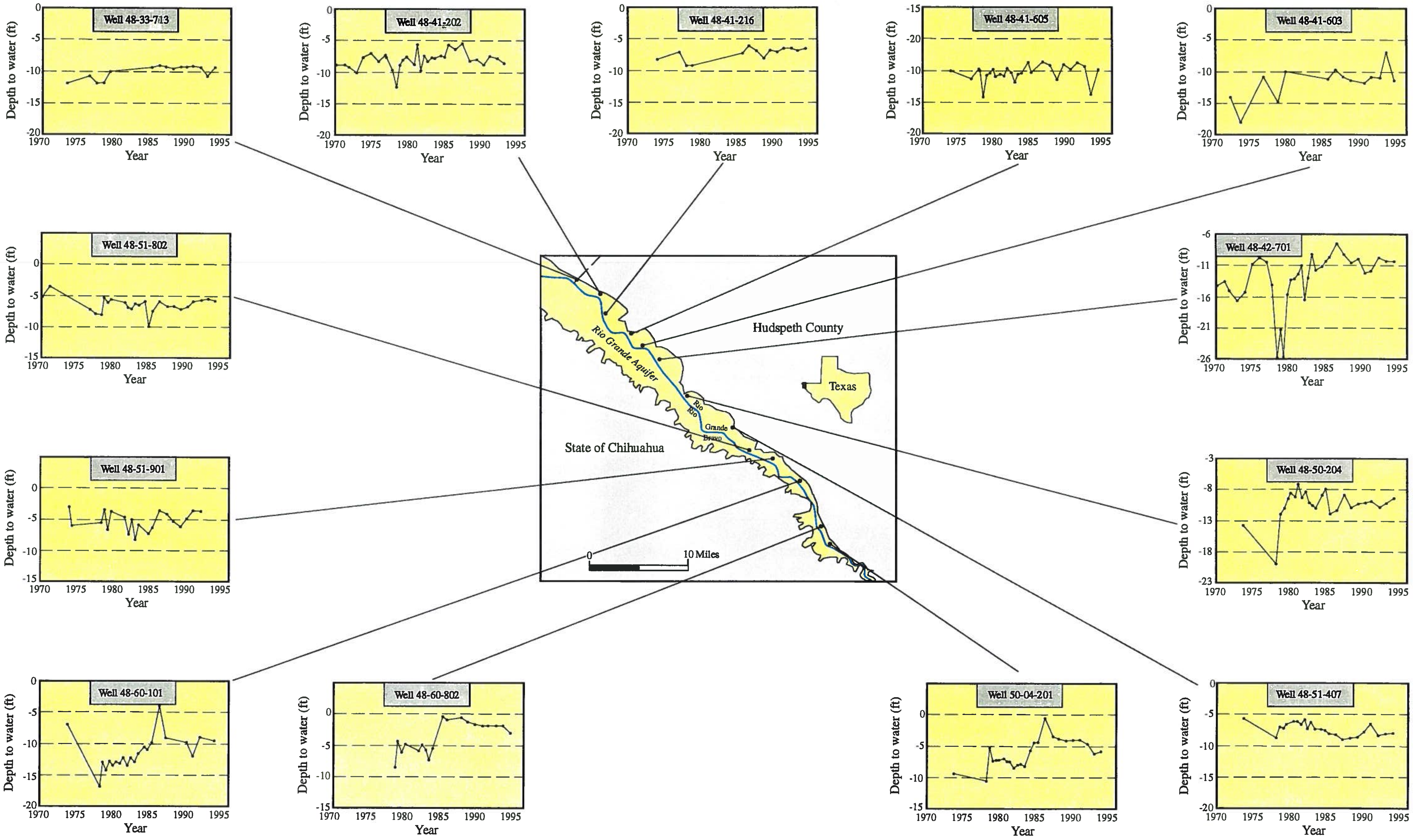

Figure 5.6. Hydrographs illustrating water-level changes in the Rio Grande aquifer in Hudspeth County between 1970 and 1995 (source of data; Texas Water Development Board).

fresh, slightly saline, and moderately saline ground water cannot be estimated accurately with available data.

Recharge Areas

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 5.7). Hydrographs indicate considerable fluctuation of a few feet to several feet in response to recharge from irrigation (Figures 5.5 and 5.6). Major ion data also shows clear evidence of direct recharge due to surface irrigation. State well 48-41-624, for example, had increasing salinities between 1986 and 1988 (Figure 5.8). When the well was resampled in 1989, total dissolved solids had decreased substantially. A chemical trilinear plot (Figure 5.8) 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, irrigation return flows, and recharge from cross-formational flow with the Hueco Bolson (Figure 5.7). Quantification of the amounts and spatial variability of recharge to the alluvial aquifer is infeasible with available data.

Information on recharge areas and ages of alluvial ground waters are provided by radioisotopes collected downstream of the El Paso/Hudspeth county line (Fisher and Mullican, 1990). Radioisotopes indicate tritiated ground water and ground water with high percentages of modern carbon (Fisher and Mullican, 1990). Tritium activities in wells screened in alluvium varied from 0.0 to 27.2 tritium units (TU), with most values greater than 10.9 TU. Most tritium data indicate a recent meteoric component in ground water, less than 50 years before present (b.p.). Carbon-14 values varied from 51 percent modern carbon (pmc) to 116 pmc and corrected ground-water ages varied from 188 to 3,489 years b.p. Isotopic results suggest mixing of modern waters (0 - 50 yrs b.p.) with slightly to moderately old waters (1,000 - 10,000 yrs b.p.).

Discharge Areas

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 5.7). The principal mode of discharge varies along the floodplain. Along the heavily urbanized Chamizal zone (Figure 5.1), discharge occurs primarily by cross-formational leakage from the alluvium to the Hueco Bolson where storage in the alluvial aquifer is depleted by 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 alluvial aquifer. From 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, in general, are kept relatively free of phreatophytes west of Fort Quitman.

Water Quality

General hydrochemistry

Few American ground-water data are available for the Rio Grande aquifer after 1979 below the El Paso narrows, so maps present dated, but fairly extensive information for the American portion of the Rio Grande alluvium. Data are current, but are somewhat limited in Mexico. Comparison of historical and current American data do not indicate significant changes in overall water quality in the alluvial aquifer between the 1970's and present; but current data are too scant to define temporal changes.

Stiff diagrams indicate Na-SO_4 ground waters in El Paso County (Figure 5.9). Below the El Paso/Hudspeth county line, chloride increasingly becomes the dominant anion in the cation/anion pairing (Figure 5.10). Mexican ground waters follow the same general trend, but show greater scatter in the segment of the floodplain across from Hudspeth County (Figures 5.9 and 5.10). 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 TDS range (Figure 5.9). Total dissolved solids are higher in alluvial deposits in Hudspeth County, falling mostly within the 3,000 to 6,000 TDS range (Figure 5.10). 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, more enriched alluvial waters.

Sources of salinity

Increasing salinities below the El Paso narrows are related to sewage outfalls, river/aquifer dynamics, and historical differences in irrigation activities. Intensive irrigation in the region began in the late 1800's. Solutes in irrigation water become concentrated in soils due to low atmospheric moisture and high evapotranspiration rates (Figure 5.11). A series of droughts in the 1940's and 1950's resulted in severe degradation of river water quality and deposition of large amounts of salts in irrigated fields (Young, 1981). These salts are readily remobilized by leaching to the shallow Rio Grande aquifer. Salts eventually return to the river.

Historical monthly water quality and streamflow data show changes in river water quality and discharge between El Paso and Fort Quitman (Figure 5.12). Spatial changes in sulfate, chloride, sodium, 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.

River salinities fluctuate spatially downstream of El Paso due to inflows from several sources that both dilute and enrich Rio Grande water with respect to total dissolved solids (Figure 5.13). Sources of dilution are principally from precipitation runoff from rural and urban areas, although sewage outflows may sometimes dilute higher TDS waters in the Rio Grande. Overall enrichment between El Paso and Fort Quitman is clearly defined. Surface water samples collected annually at El Paso and Fort Quitman indicate very little scatter of water quality constituents. Grouping of analyses fall into distinct clusters (Figure 5.14). The "El Paso" and "Fort Quitman" clusters correspond generally to evolutionary trends in the Rio Grande aquifer in El Paso County and Hudspeth County, respectively (Figure 5.15). Despite wide scatter in Rio Grande aquifer data (Figure 5.15), 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.

Increasing salinities in both the river and Rio Grande aquifer along the downstream trend generally reflects the tendency for salts to be recycled in irrigation water, to return to the Rio Grande, and then to be reapplied to crops (Figure 5.13). Near El Paso, relatively dilute irrigation waters are enriched by evaporation and leaching when applied to crops. Enriched return flows are reapplied to crops downstream. By this process, the salinities in the Rio Grande and the Rio Grande aquifer increase in a perpetual manner downstream, and elevated salinities in the Rio Grande result in elevated salinities in the Rio Grande aquifer (and vice versa). This process is a basic function of evapotranspiration, con-

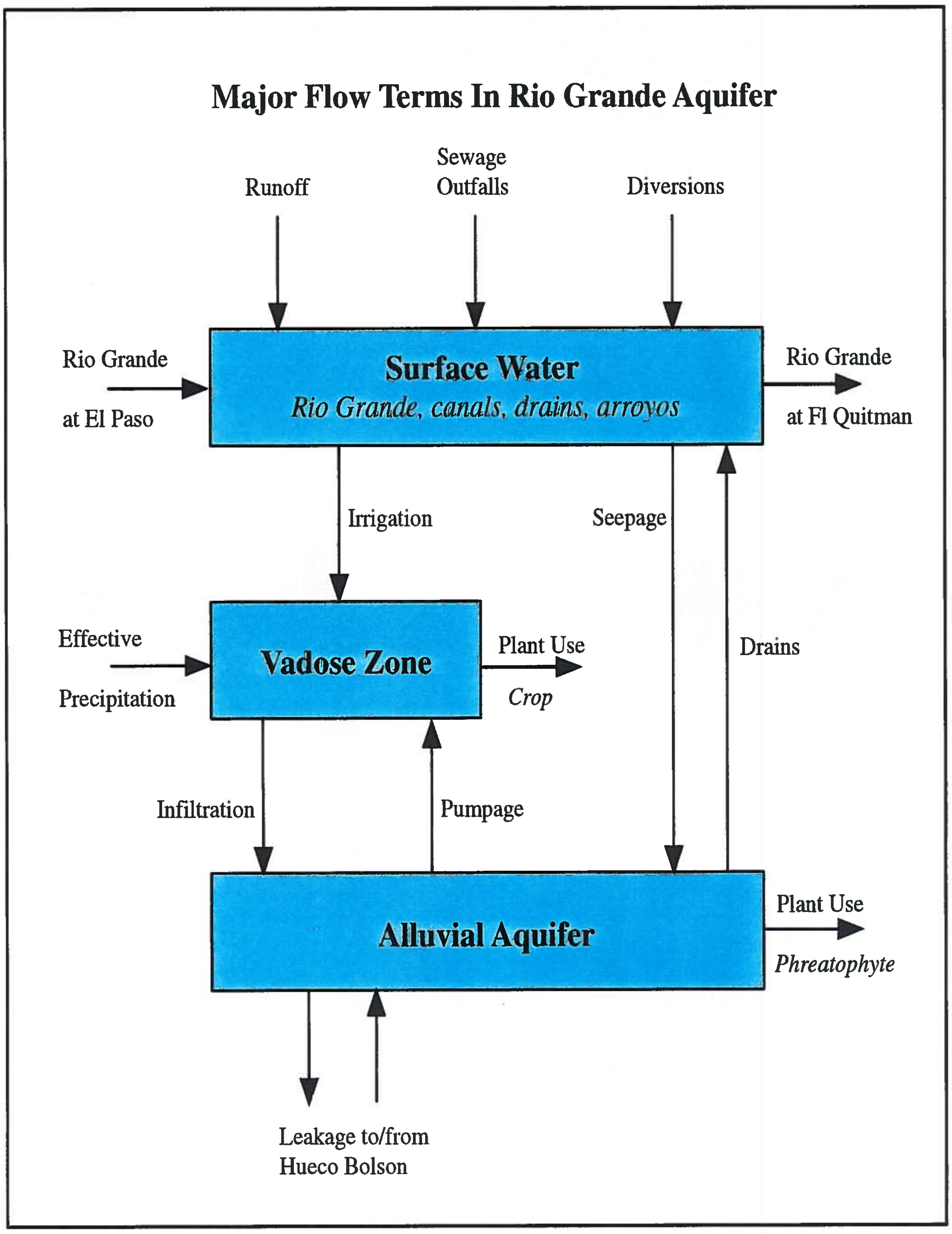

Figure 5.7. Major flow components in the Rio Grande aquifer.

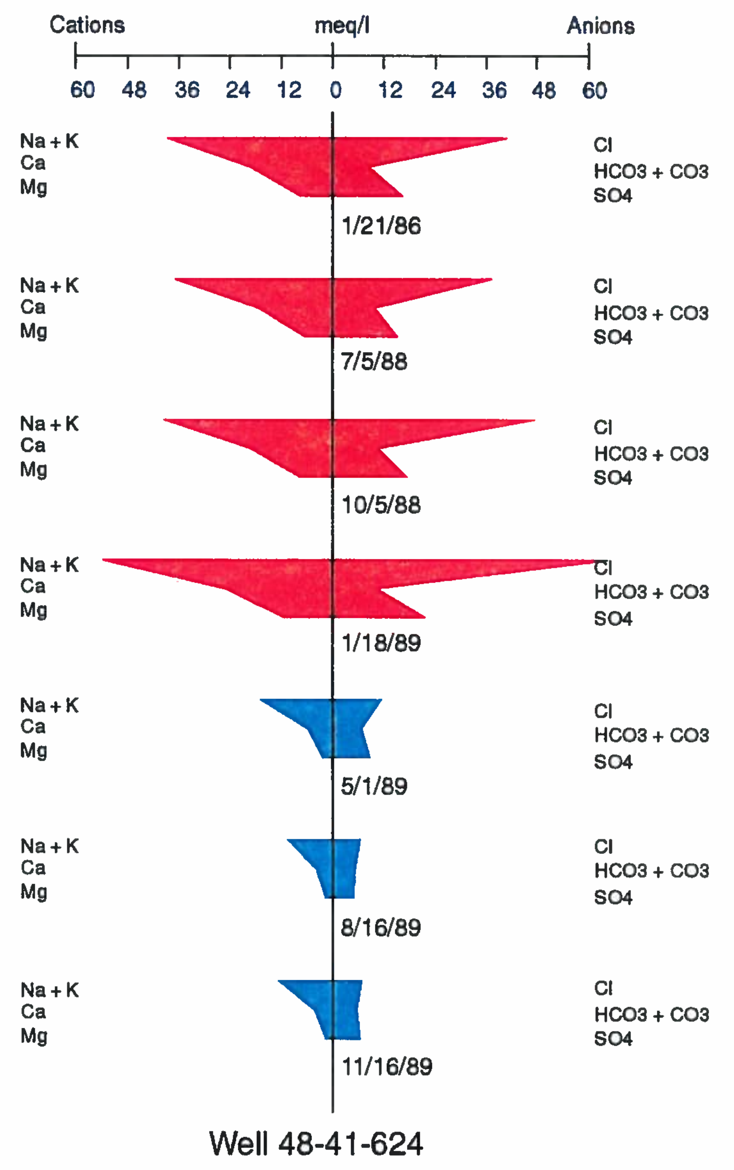

Figure 5.8a. Located adjacent to the Rio Grande, well 48-41-624 had increasing total dissolved solids in samples collected between 1986 and 1989. When the well was resampled in May, 1989, total dissolved solids had decreased substantially (source of data, Texas Water Development Board).

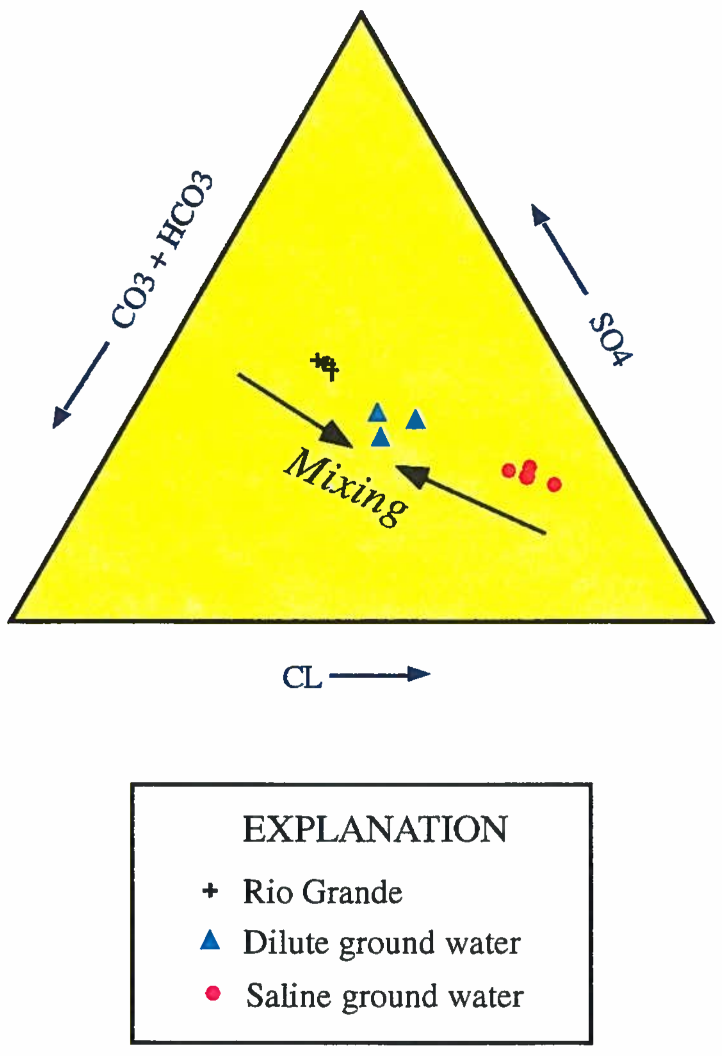

Figure 5.8b. The trilinear plot shows enriched well samples from Figure 5.8a (1986 - 1989), dilute well samples (May, 1989 and later), and Rio Grande samples collected in 1989. Results indicate dilution of ground water due to mixing with Rio Grande water (source of data, Texas Water Development Board).

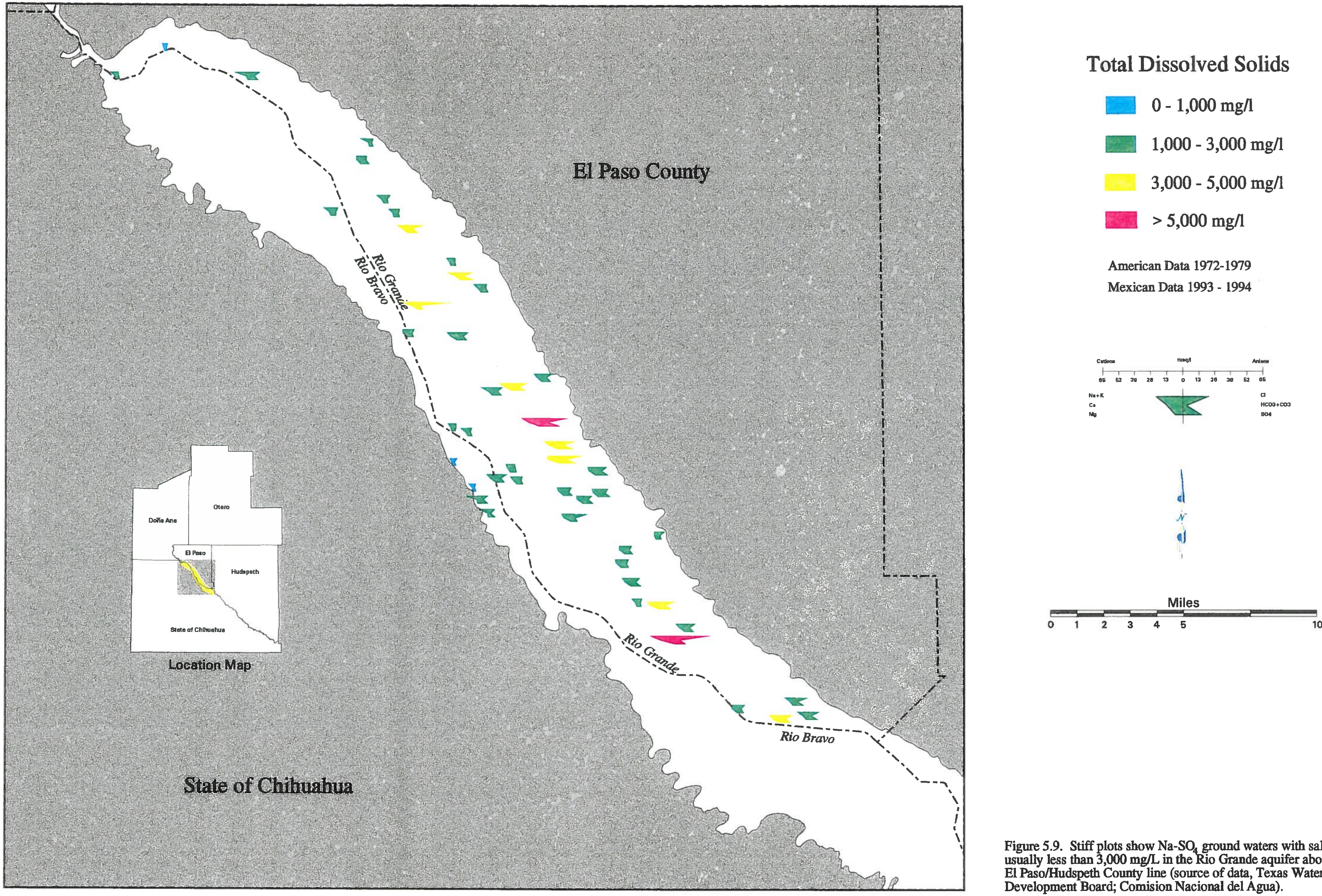

Figure 5.9. Stiff plots show Na-SO_4 ground waters with salinities usually less than 3,000 mg/L in the Rio Grande aquifer above the El Paso/Hudspeth County line (source of data, Texas Water Development Board; Comision Nacional del Agua).

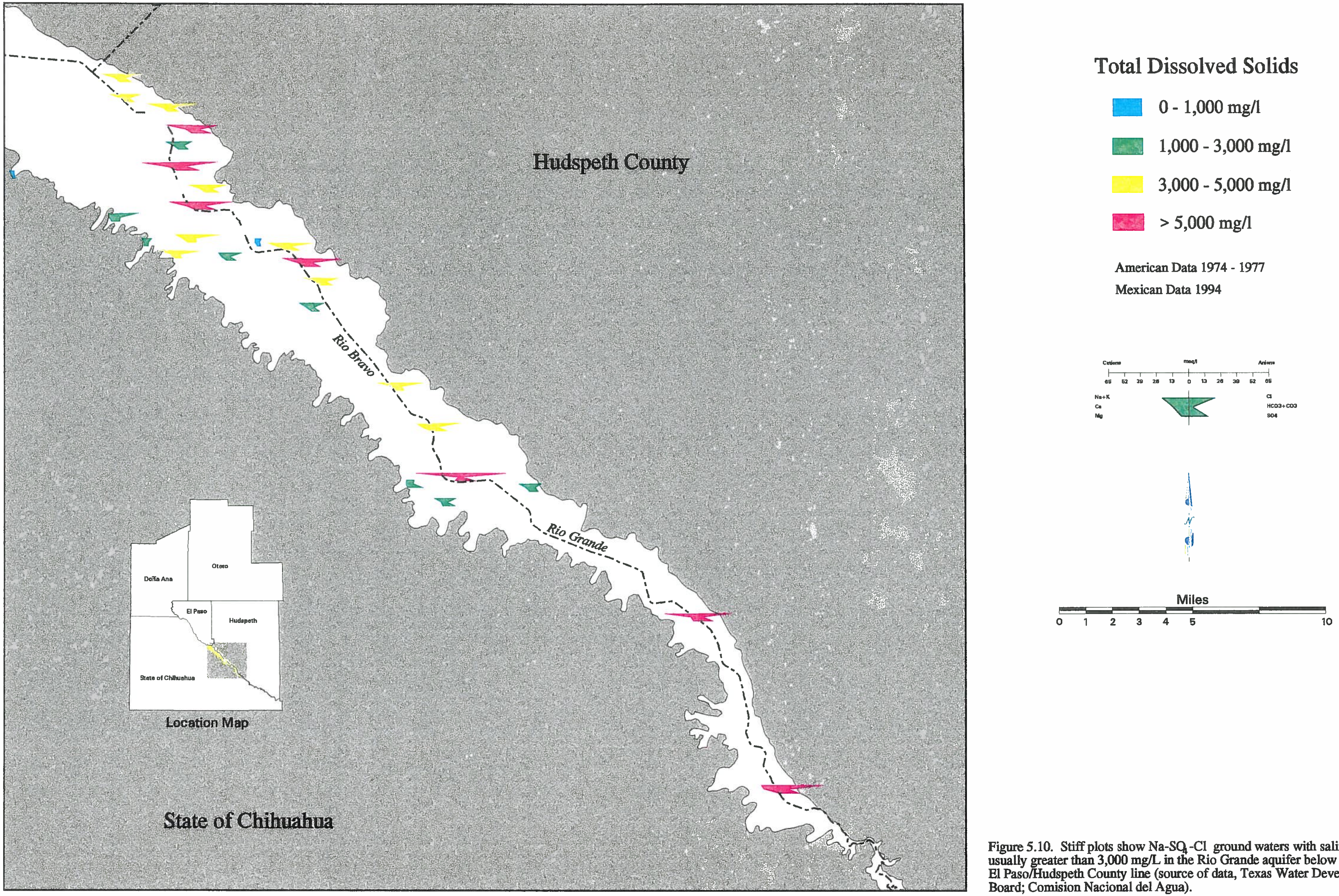

Figure 5.10. Stiff plots show Na-SO_4-Cl ground waters with salinities usually greater than 3,000 mg/L in the Rio Grande aquifer below the El Paso/Hudspeth County line (source of data, Texas Water Development Board; Comision Nacional del Agua).

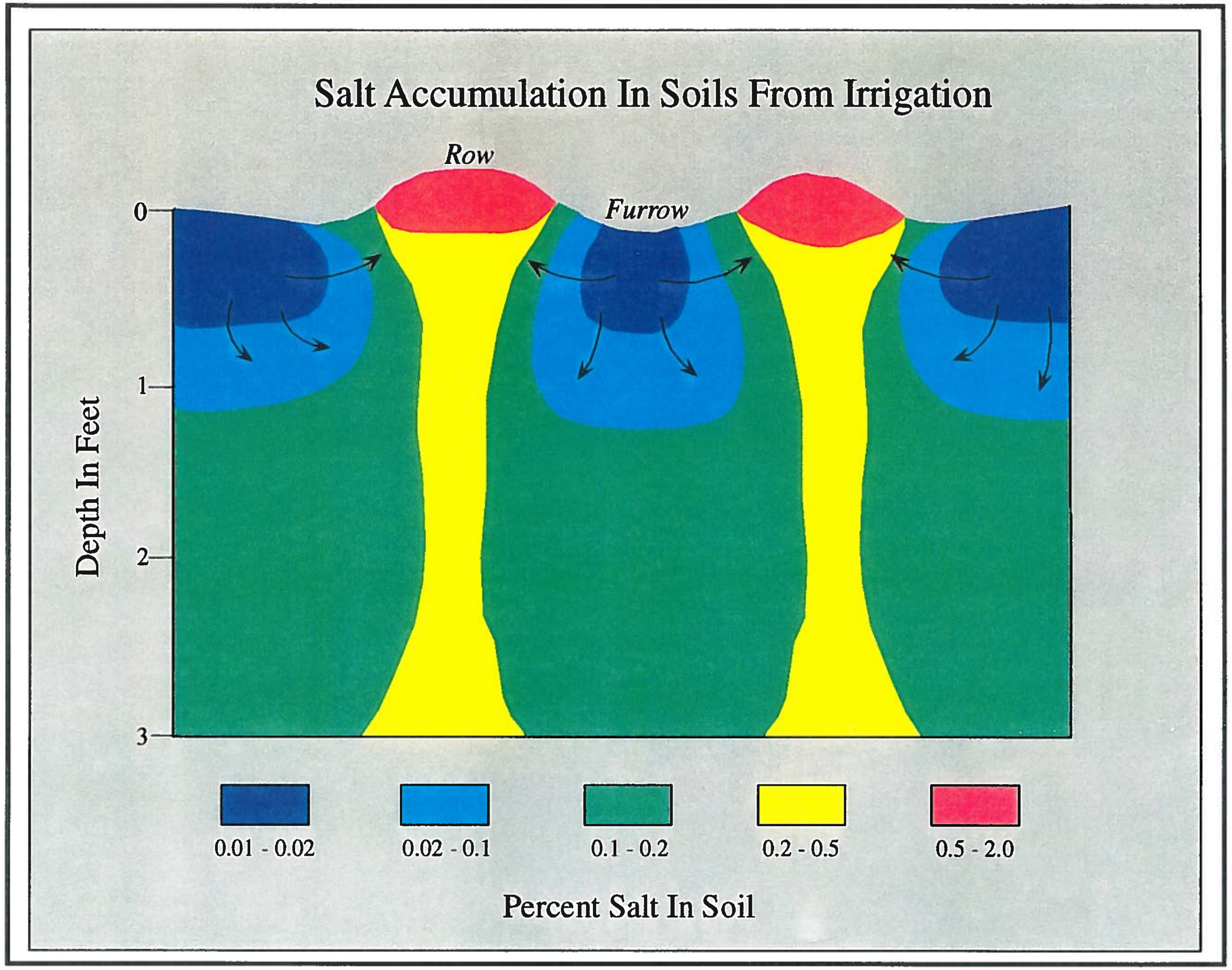

Figure 5.11. Diagram showing how dissolved salts in irrigation water become concentrated in irrigated soils due to high evapotranspiration rates (modified from Longnecker and Lyerly, 1959).

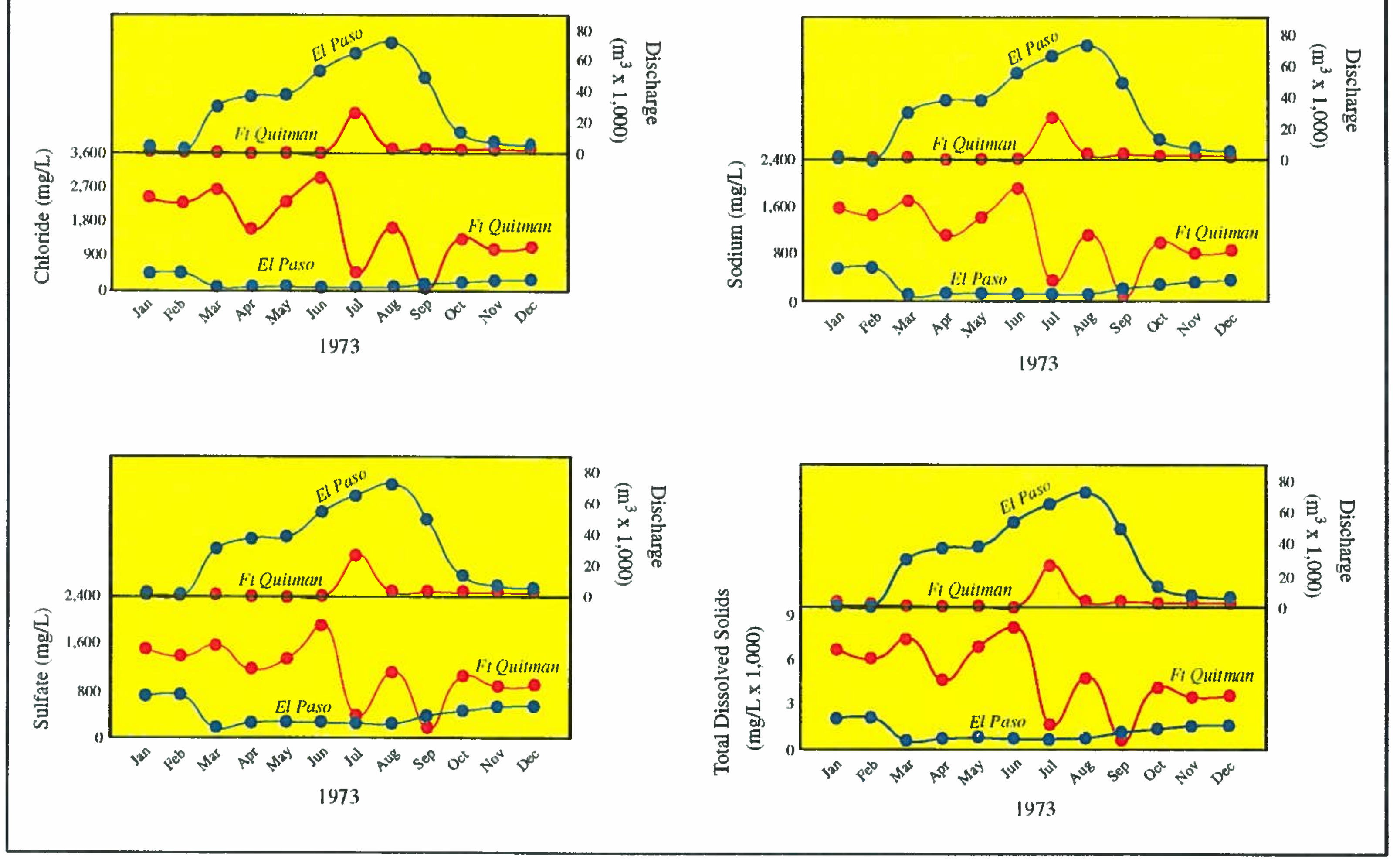

Figure 5.12a. Diagram comparing water quality and streamflow discharge for the Rio Grande at El Paso and Ft Quitman, 1973. Spatial changes in Cl, SO_4, Na, and TDS for most months indicate appreciable decline in surface-water quality downstream of El Paso. Water quality improves when discharge is high 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").

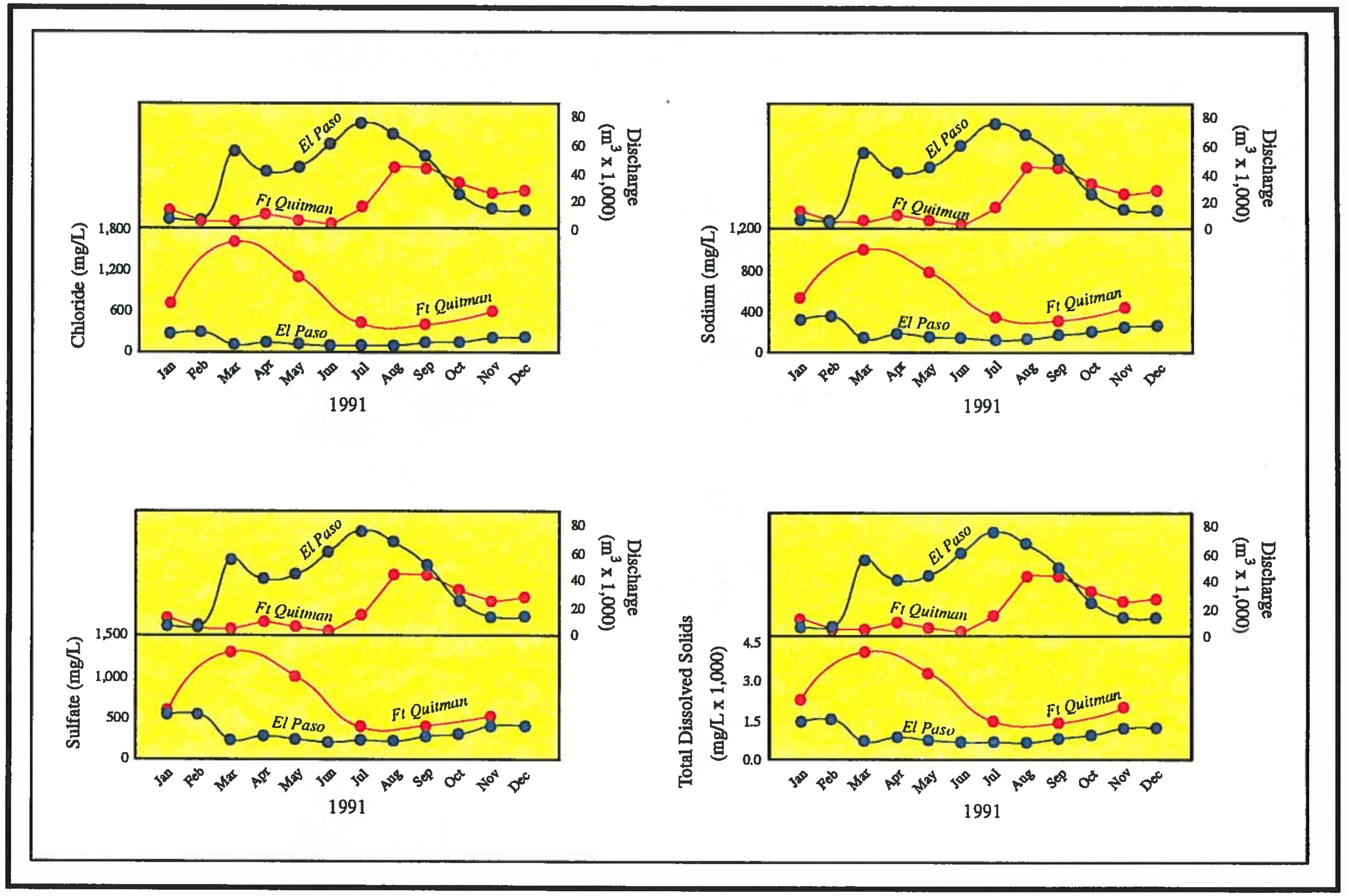

Figure 5.12b. Diagram comparing water quality and streamflow discharge for the Rio Grande at El Paso and Ft Quitman, 1991. Spatial changes in Cl, SO_4, Na, and TDS for most months indicate appreciable decline in surface-water quality downstream of El Paso. Water quality improves when discharge is high 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").

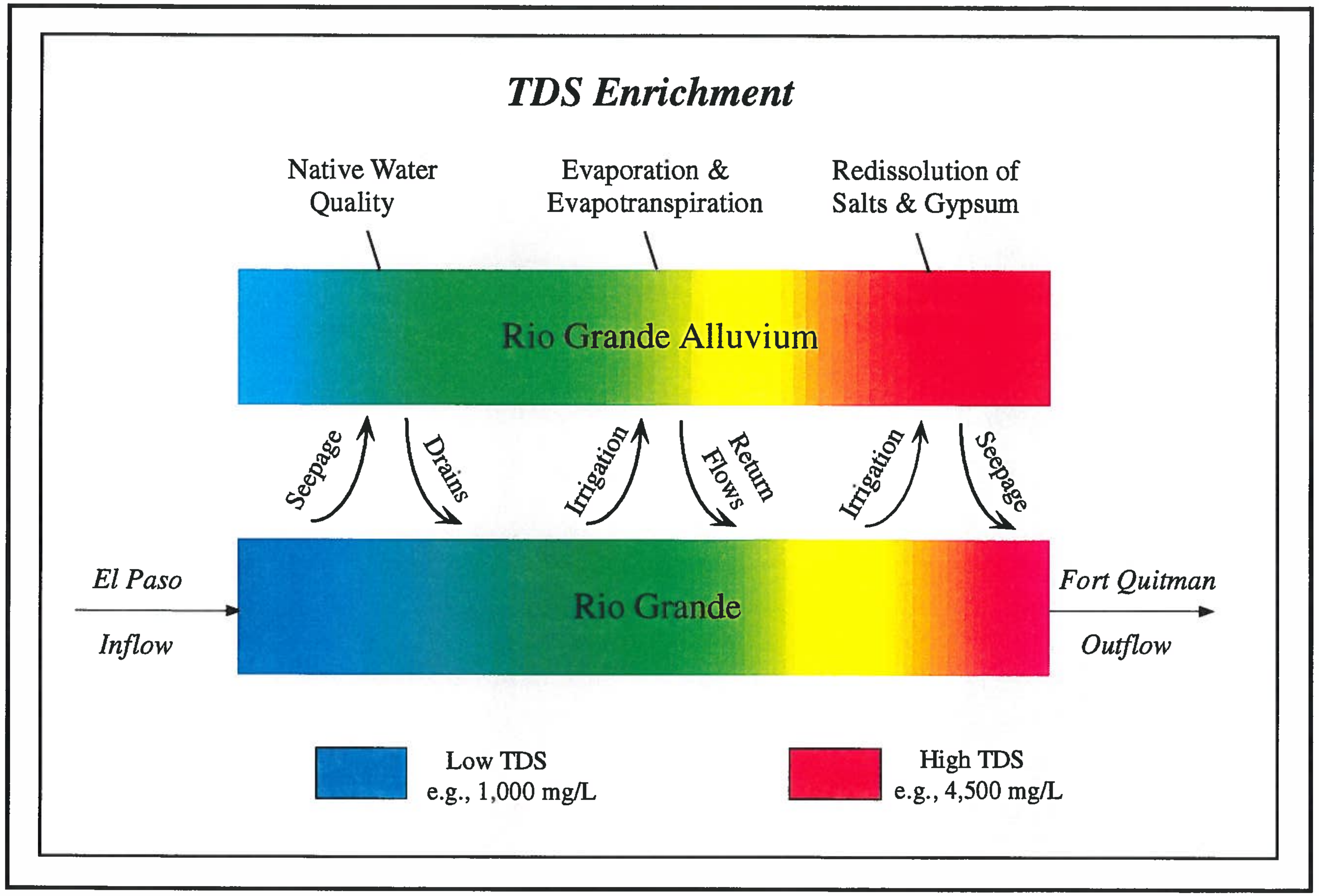

Figure 5.13. River salinities fluctuate downstream of El Paso due to inflows from several sources that both dilute and enrich Rio Grande water with respect to total dissolved solids. An overall pattern of salt water enrichment occurs between El Paso and Fort Quitman.

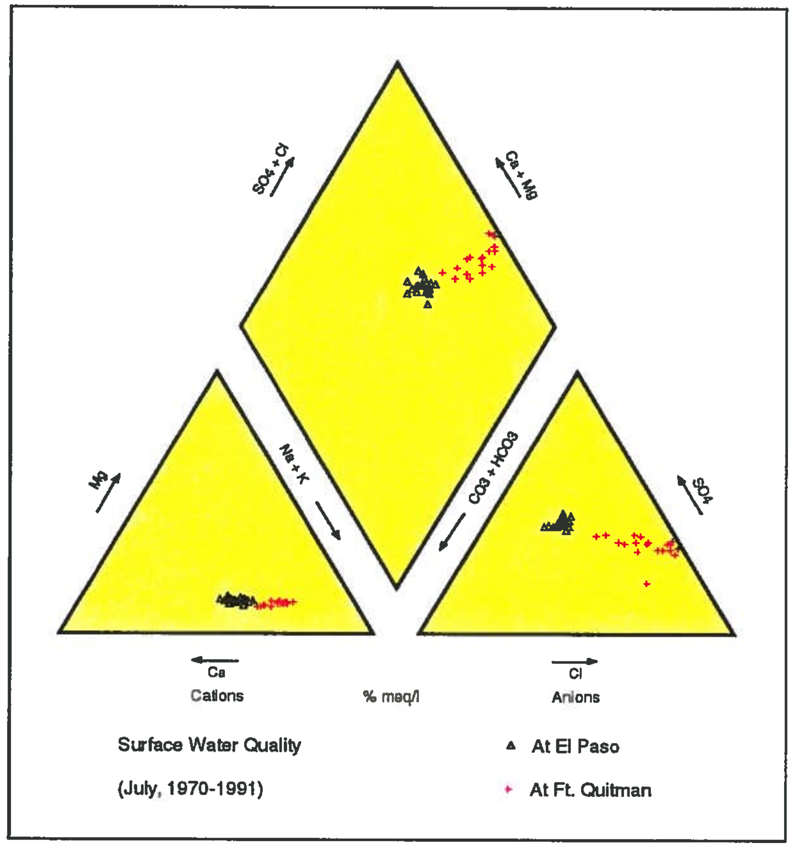

Figure 5.14a. Piper diagram shown in time series that illustrates surface water at the El Paso and Fort Quitman gage stations, January, 1970 - 1991. Surface water groups into distinct clusters of different hydrochemical types at the two gage stations (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

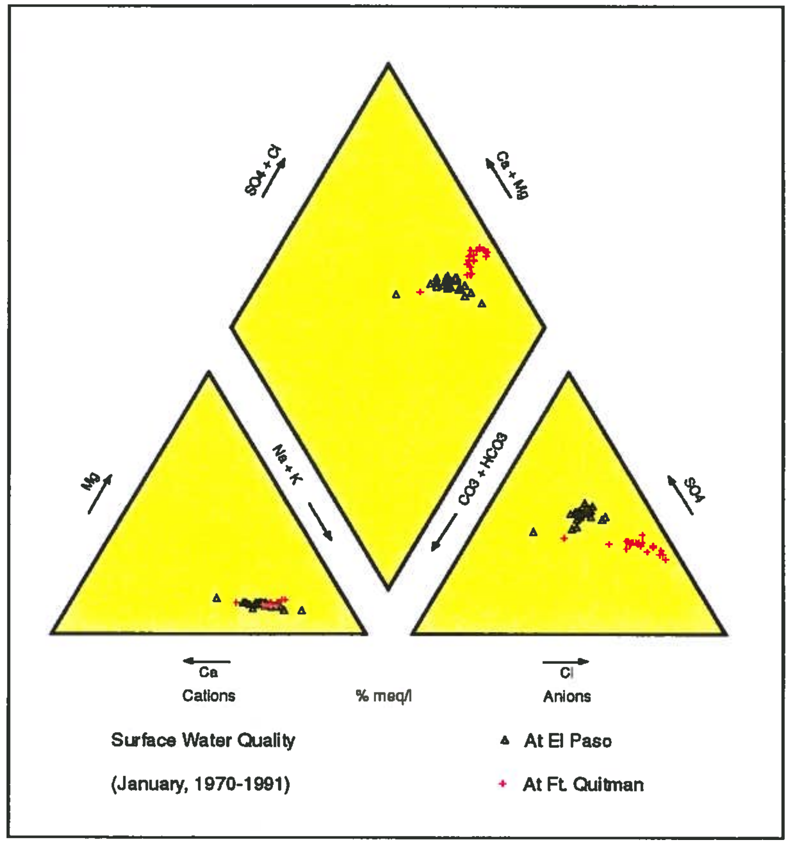

Figure 5.14b. Piper diagram shown in time series that illustrates surface water at the El Paso and Fort Quitman gage stations, July, 1970 - 1991. Surface water groups into distinct clusters of different hydrochemical types at the two gage stations (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

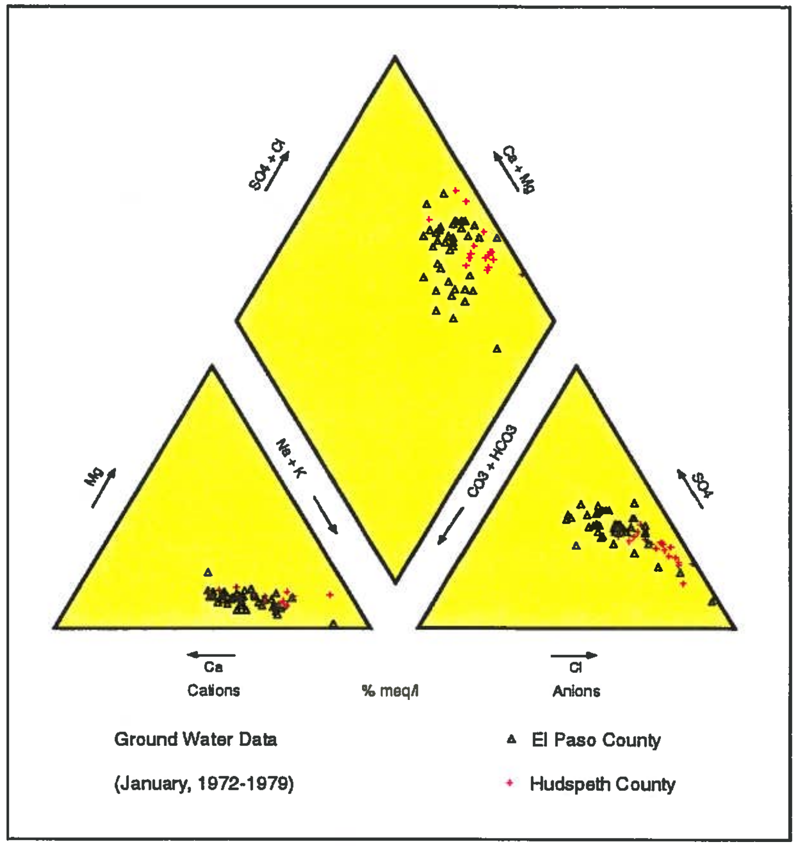

Figure 5.15. Piper diagram for the Rio Grande aquifer in El Paso and Hudspeth counties. These data indicate a clear relationship to surface water quality (Figure 5.14) at El Paso and Fort Quitman (source of data, Texas Water Development Board).

sumptive use, and enriched return flow (Figures 5.13 and 5.16).

Evaporation of water in the Mexican part of the Rio Grande aquifer is indicated clearly with stable isotope data (Figure 5.17). These data (Payne, 1976) indicate evaporative enrichment of alluvial ground water, probably during application of irrigation water to irrigable crops. Enrichment of soil water with heavier stable isotopes, and simultaneous enrichment of salts in soil water occurs as a result of evapotranspiration of water from soil profiles, and leaching of salts and enriched soil water to the shallow water table.

Stream and canal seepage act to partially control salinities. Where there is seepage from rivers and canals to the alluvial aquifer, especially between the Chamizal zone and county line, the seepage helps to maintain dilute concentrations in the aquifer. Along this reach, the heads in the Rio Grande aquifer are generally equal to or below the head in the stream. This favors direct seepage to the alluvial aquifer, especially when river stage is high due to irrigation releases, or flood stage. Below the El Paso/Hudspeth county line, heads in the alluvial aquifer tend to be slightly higher than heads in the river during normal stage. This condition minimizes direct seepage from the river, except when stream stage is abnormally high.

Upwelling waters from undeveloped portions of the Hueco-Tularosa aquifer and southeastern Hueco aquifer may dilute or enrich Rio Grande water with respect to dissolved solids, depending on the spatial variability of salinity in each aquifer. The data appear to indicate that dilution of Rio Grande water occurs in the Fabens artesian zone. Data in other areas are insufficient to determine effects of cross-formational flow on salinities.

Origin of solutes

Understanding the origin of natural solutes in the aquifer is a first step in deciphering anthropogenic contamination. A discussion of the origin of solutes in the Rio Grande aquifer is therefore provided.

Changing ion ratios with increasing chlorinity (i.e., salinity) are the most conspicuous hydrochemical trends in the aquifer. (Na/Cl) molar ratios decrease from 2.4 to 0.6 with increasing chlorinity (Figure 5.18). (Na/Cl) ratios greater than 1.0 at low chlorinities are partly due to excess sodium in infiltrating river waters. (Na/Cl) ratios are slightly higher in the aquifer and recharge by river water cannot account for all of the excess sodium in the aquifer. Clay particles are probably adsorbing calcium and magnesium in solution in exchange for bound sodium. At lower chlorinities (< 35 mmols/L Cl), the reversible ion exchange reactions are:

$$Na_2\text{-clay} + Ca^{+2} = Ca\text{-clay} + 2Na^{+} \qquad (5.1)$$

$$Na_2\text{-clay} + Mg^{+2} = Mg\text{-clay} + 2Na^{+} \qquad (5.2)$$

With increasing chlorinity, the (Na/Cl) ratios decrease (Figure 5.18). A molar ratio close to 1.0 indicates halite dissolution:

$$NaCl = Na + Cl \qquad (5.3)$$

(Na/Cl) ratios are usually less than 1.0 for chlorinities greater than 35 mmols/L Cl (Figure 5.18). This indicates that ground waters are not evolving towards complete equilibrium with halite. The (Ca +Mg)/ HCO_3 molar ratios increase with chlorinity (Figure 5.19). Calcium and magnesium are being added to solution at a greater rate than bicarbonate. The (Ca + Mg)/HCO_3 ratio would be less than or equal to 0.5 if magnesium and calcium originate solely from the dissolution of carbonate minerals in alluvial sediments or cement, as indicated by the governing equations:

For calcite dissolution ([Ca + Mg]/HCO_3 = 0.5):

$$CaCO_3 + H_2O + CO_2 = Ca + 2HCO_3 \qquad (5.4)$$

For dolomite dissolution ([Ca + Mg]/HCO_3 = 0.5):

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O =$$

$$Ca + Mg + 4HCO_3 \qquad (5.5)$$

Having (Ca + Mg)/HCO_3 ratios greater than 0.5 at higher chlorinities indicates an additional source of calcium and/or magnesium (Figure 5.19). A possible source of excess calcium could come from dissolution of gypsum:

$$CaSO_4 \bullet 2H_2O = Ca + SO_4 + 2H_2O \qquad (5.6)$$

or reversible ion exchange:

$$Ca\text{-clay} + 2Na = Na_2\text{-clay} + Ca^{+2} \qquad (5.7)$$

Average (Ca/SO_4) ratios do not change for the full range of chlorinity (Figure 5.20), suggesting that (1) gypsum dissolution is the primary source of calcium at increasing salinities (releasing 1 equivalent calcium for 1 equivalent sulfate), and that (2) calcium is not substantially liberated by ion exchange. Reaction 5.6, instead of reaction 5.7 is the primary source of most of the additional calcium.

(Na/Cl) molar ratios less than 1.0 at chlorinities greater than 35 mmols/L Cl (Figure 5.18) probably result from the loss of sodium for bound magnesium:

$$Mg\text{-clay} + 2Na^{+} = Na_2\text{-clay} + Mg^{+2} \qquad (5.8)$$

(Mg/SO_4) ratios show an additional source of magnesium with increasing chlorinity (Figure 5.21), supporting the hypothesis of exchange of bound magnesium for sodium (reaction 5.8). That sodium is exchanged preferentially for bound magnesium (in lieu of bound calcium) is a function of the low selectivity coefficient for the magnesium versus calcium exchange pair. Valid for large ranges of ratios of magnesium to calcium and ionic strength, selectivity coefficients are typically in the range 0.6 to 0.9 (Jensen and Babcock, 1973) indicating that magnesium is released preferentially in clays in exchange for sodium in solution.

These analyses, along with stable isotopes (Figure 5.17) indicate evolution of water chemistry from a dilute, $Na\text{-}SO_4$ water that is similar in composition to Rio Grande water, to a more concentrated $Na\text{-}Cl\text{-}SO_4$ water through a number of simple chemical reactions and processes:

- Evaporation of water.
- Exchange of calcium and magnesium for bound sodium at chlorinities lower than 35 to 40 mmols/L Cl.
- Reverse exchange of sodium for bound magnesium and calcium by cation exchange at chlorinities greater than 35 to 40 mmols/L Cl, preference to magnesium exchange due to the Mg/Ca selectivity coefficient.
- Dissolution of halite and gypsum for the full range of salinities.

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 5.14 and 5.15). 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 5.22). 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.

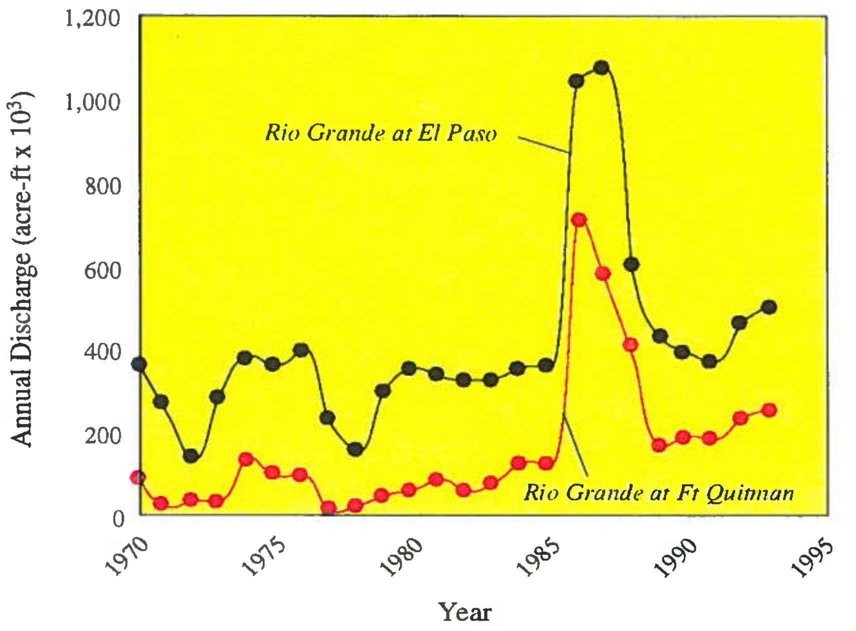

Figure 5.16. Comparison of discharge quantities in the Rio Grande at El Paso and Fort Quitman. Substantial loss of discharge is due to evapotranspiration by crops and other consumptive uses that tend to concentrate salts in fields and to enrich return flows with respect to total dissolved solids (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

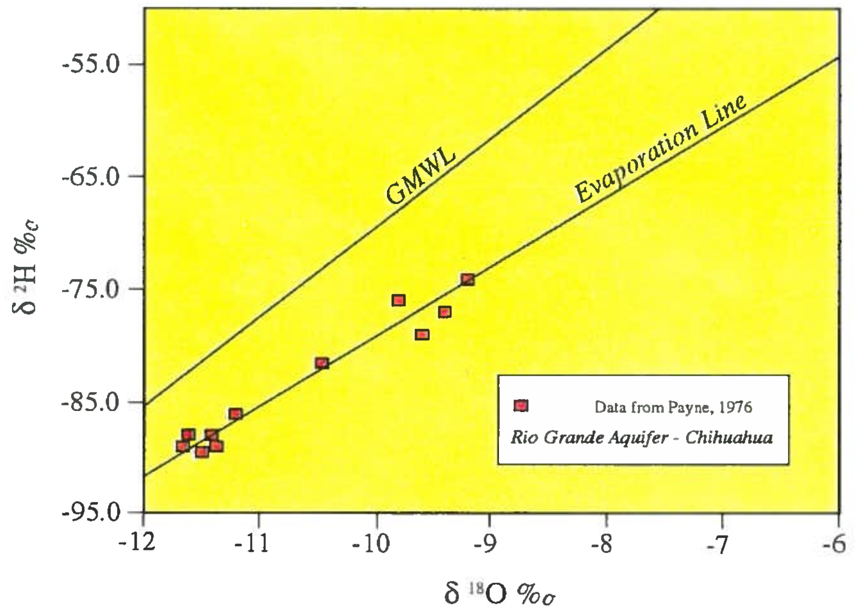

Figure 5.17. Binary plot of δ^2H versus δ^{18}O values for Rio Grande aquifer waters in the Mexican part of the alluvial aquifer. Stable hydrogen and oxygen isotope ratios in ground waters plot along the evaporation line, indicating evaporative enrichment of water, probably during irrigation (source of data, Payne, 1976).

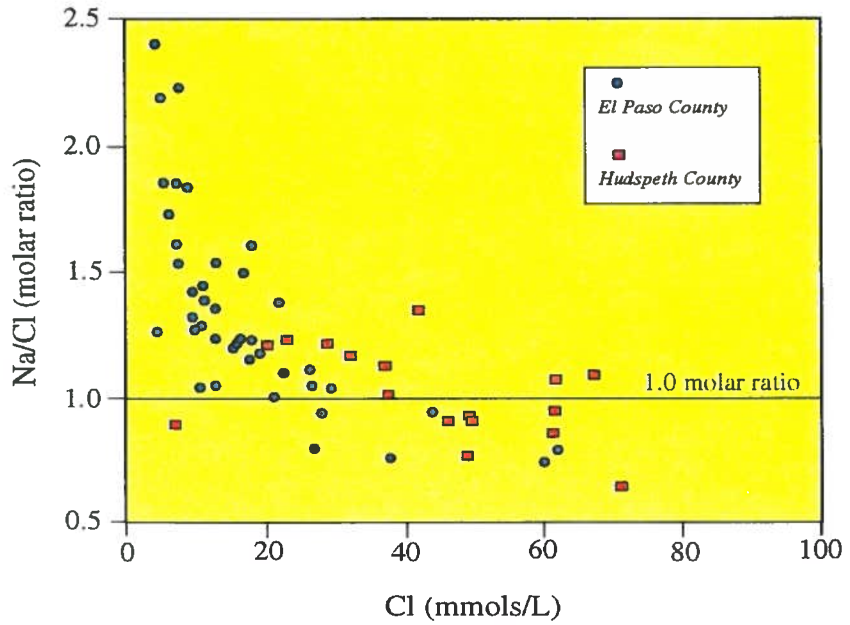

Figure 5.18. Scatter plot showing (Na/Cl) molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. (Na/Cl) molar ratios decrease from 2.4 to 0.6 with increasing chlorinity (source of data, Texas Water Development Board).

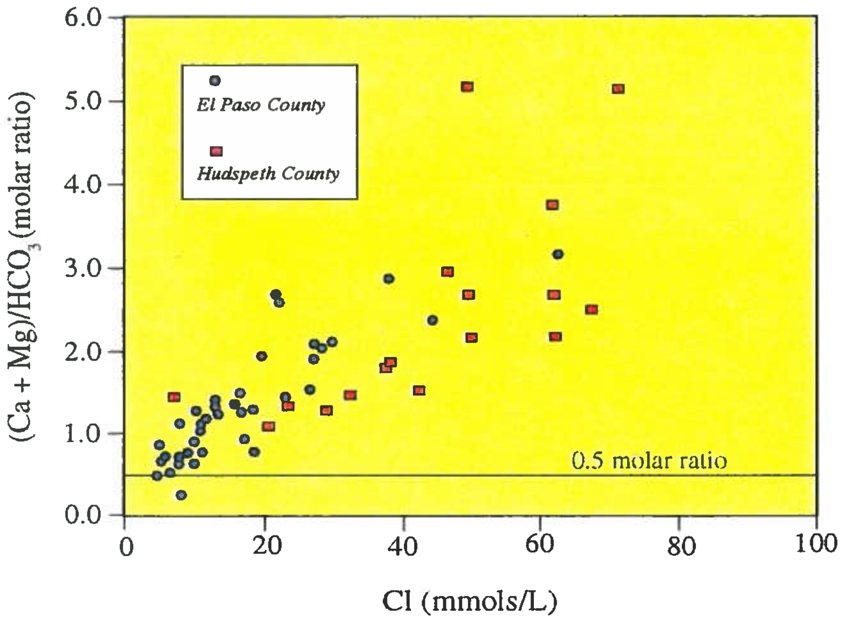

Figure 5.19. Scatter plot showing (Ca+Mg)/HCO_3 molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. Points above the 0.5 ratio line indicate a source of calcium and/or magnesium other than dissolution of carbonate rock (source of data, Texas Water Development Board).

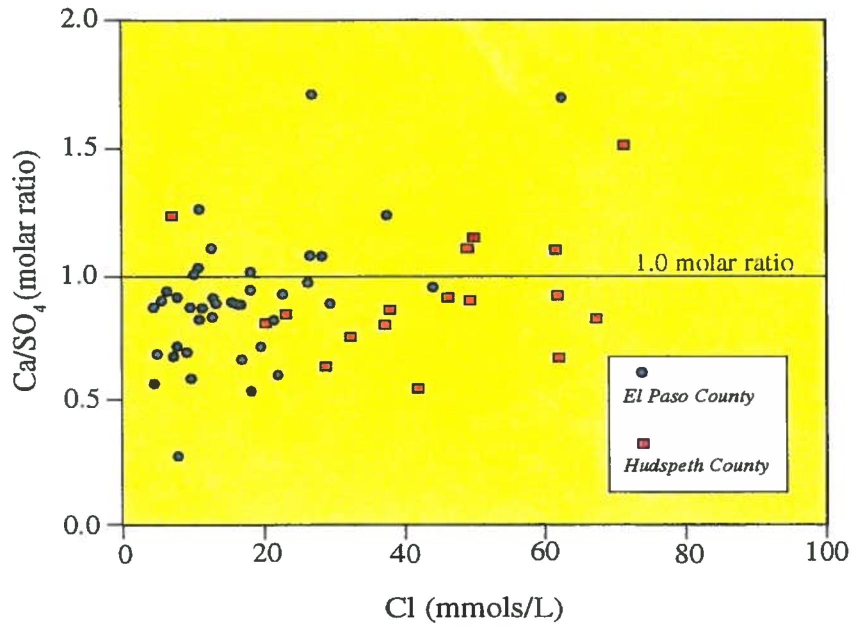

Figure 5.20. Scatter plot showing (Ca/SO_4) molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. Average (Ca/SO_4) ratios do not change with increasing chlorinity (source of data, Texas Water Development Board).

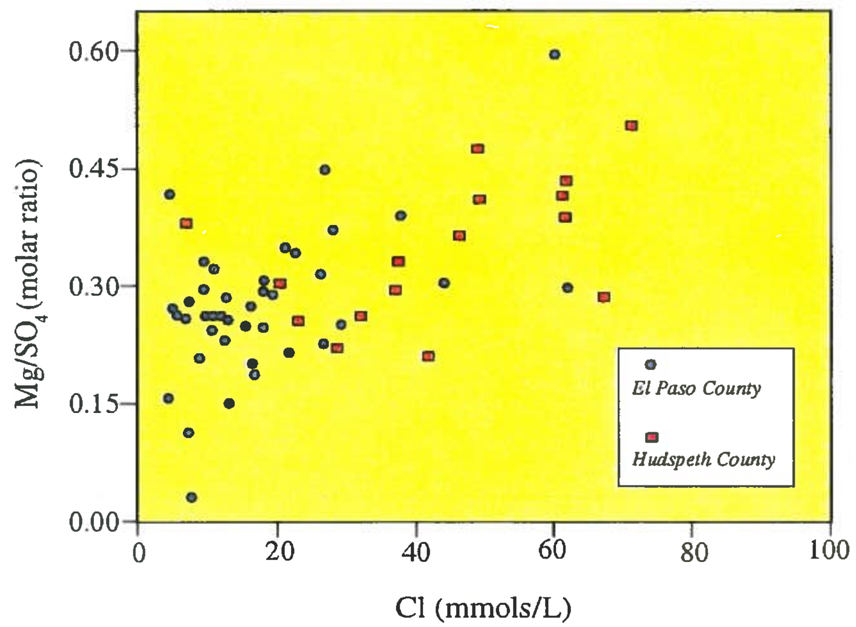

Figure 5.21. Scatter plot showing (Mg/SO_4) molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. Average (Mg/SO_4) ratios increase with increasing chlorinity, suggesting an additional source of Mg (source of data, Texas Water Development Board).

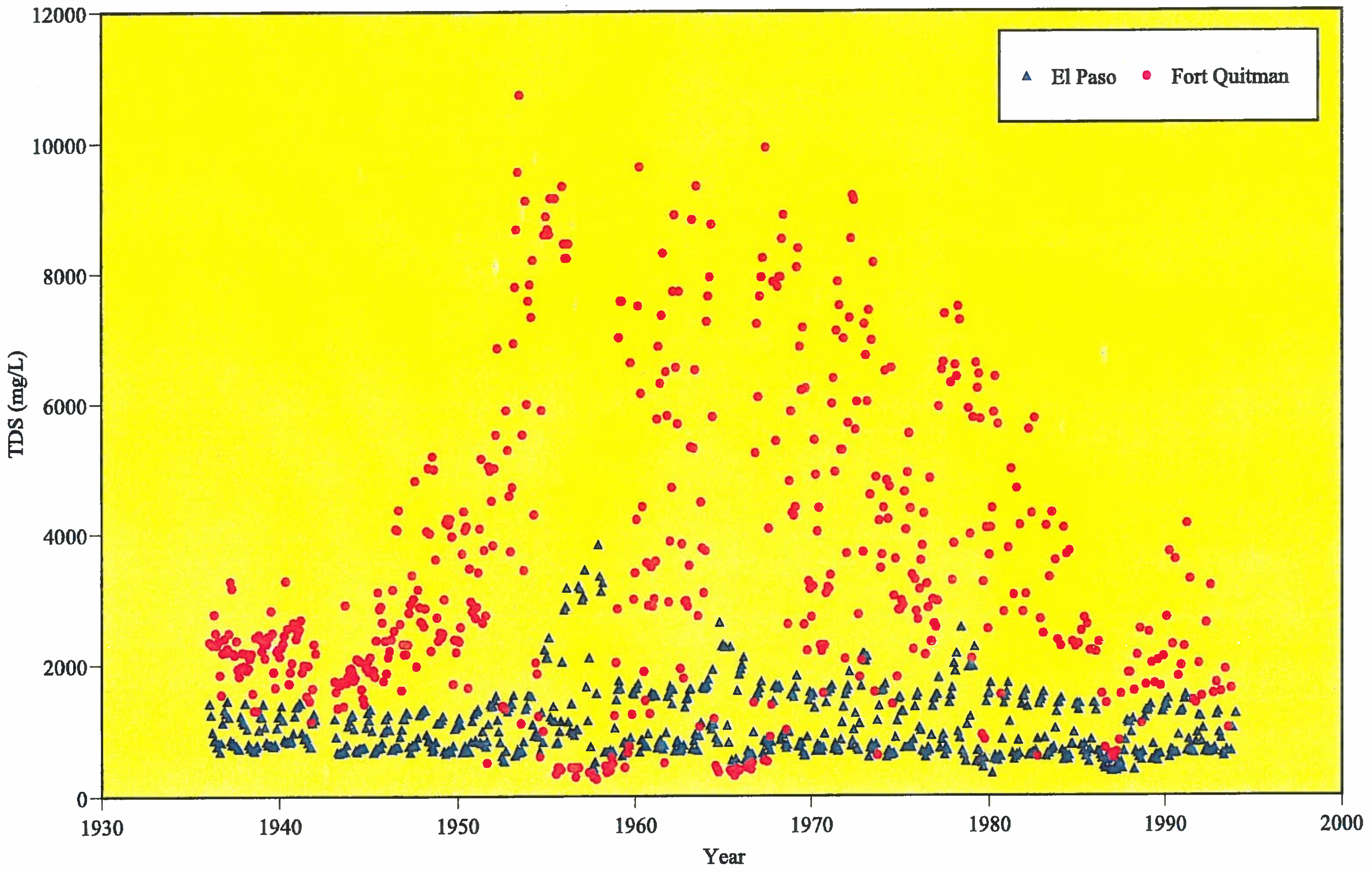

Figure 5.22. Time series graph of increasing salinities in the Rio Grande (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

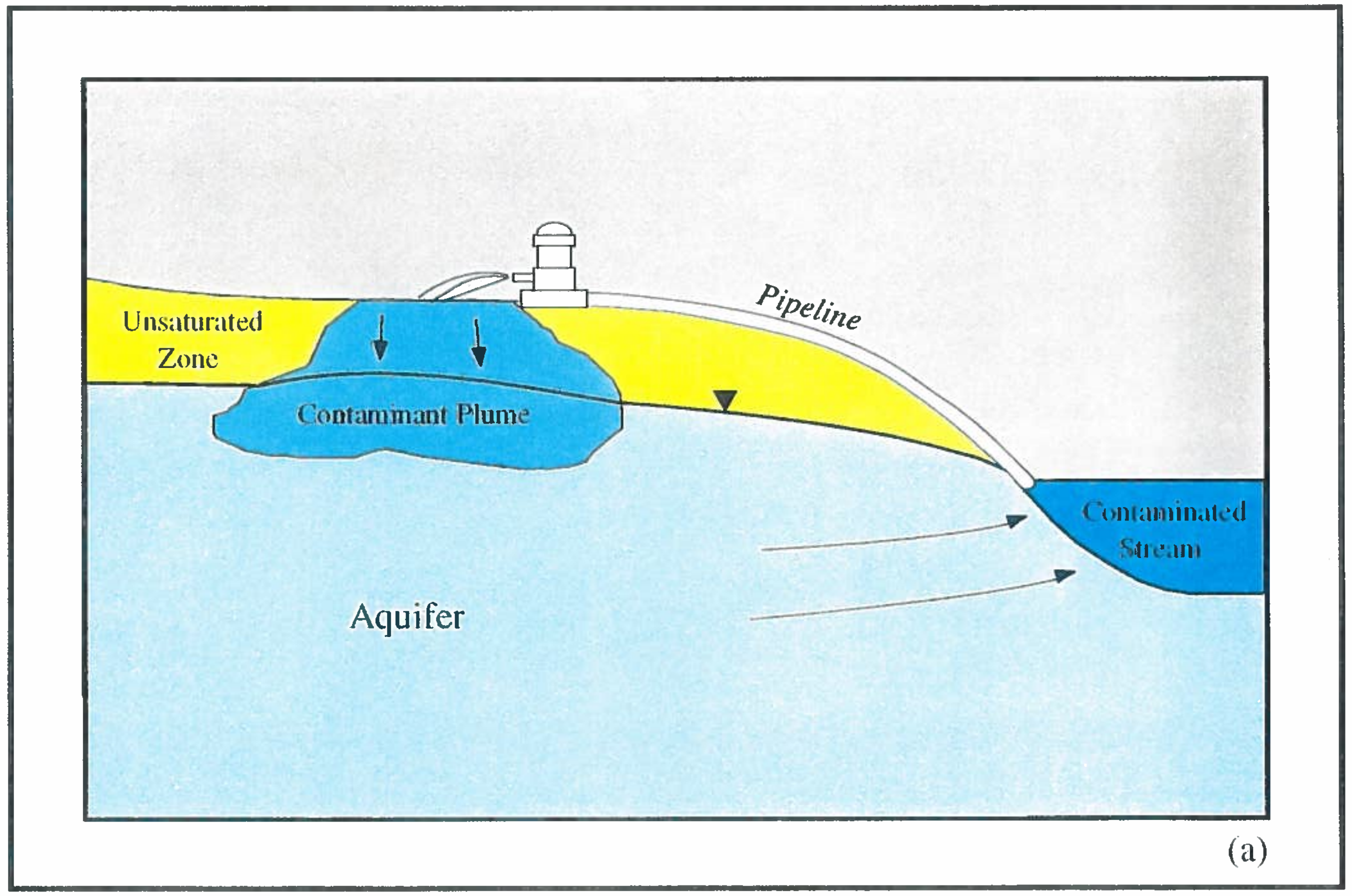

Figure 5.23a. Diagram illustrating contamination of an alluvial aquifer from a contaminated stream. Direct application of surface water may contaminate the aquifer.

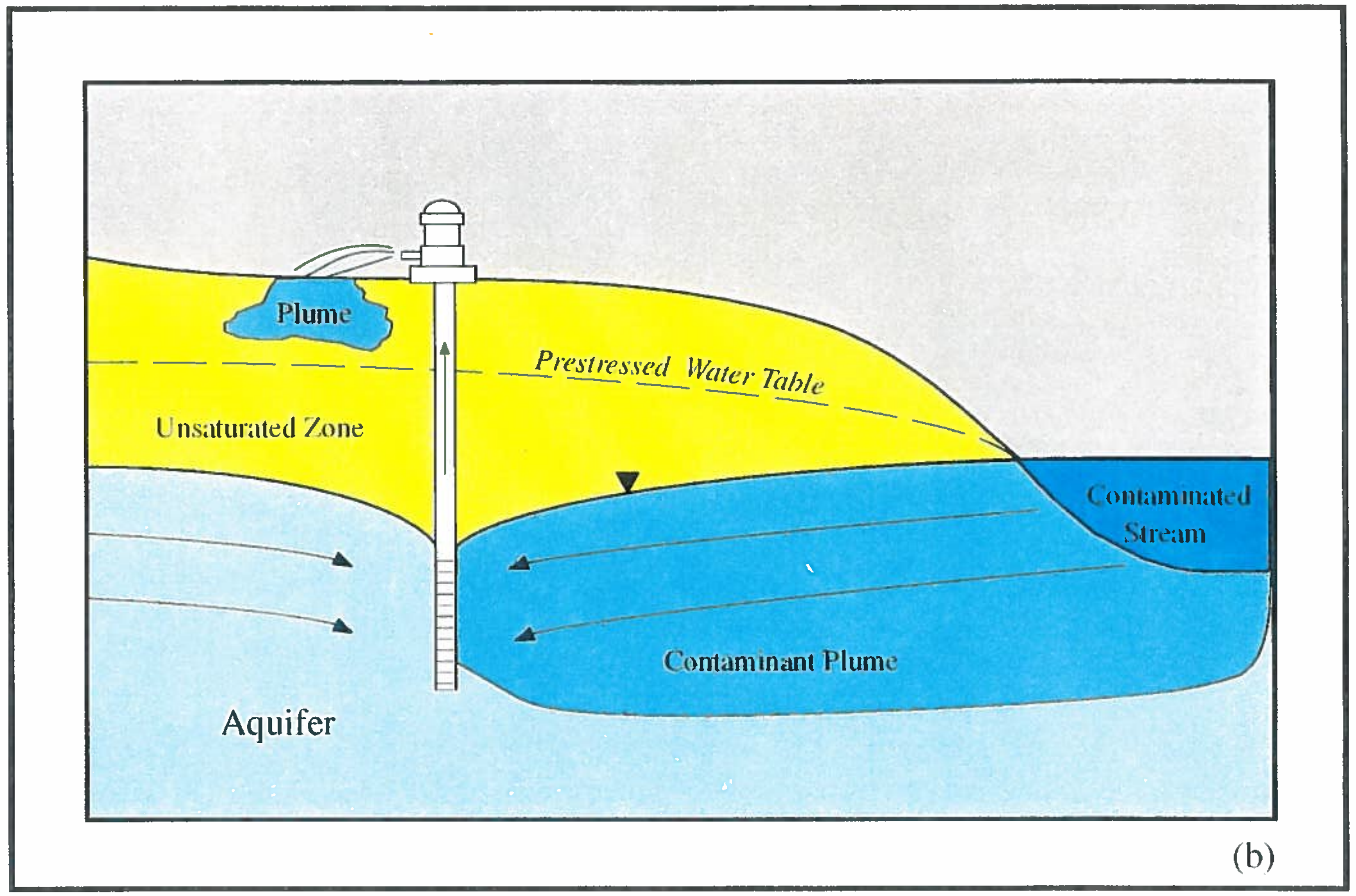

Figure 5.23b. Diagram illustrating contamination of an alluvial aquifer from a contaminated stream. Induced infiltration of contaminated surface water may contaminate the aquifer.

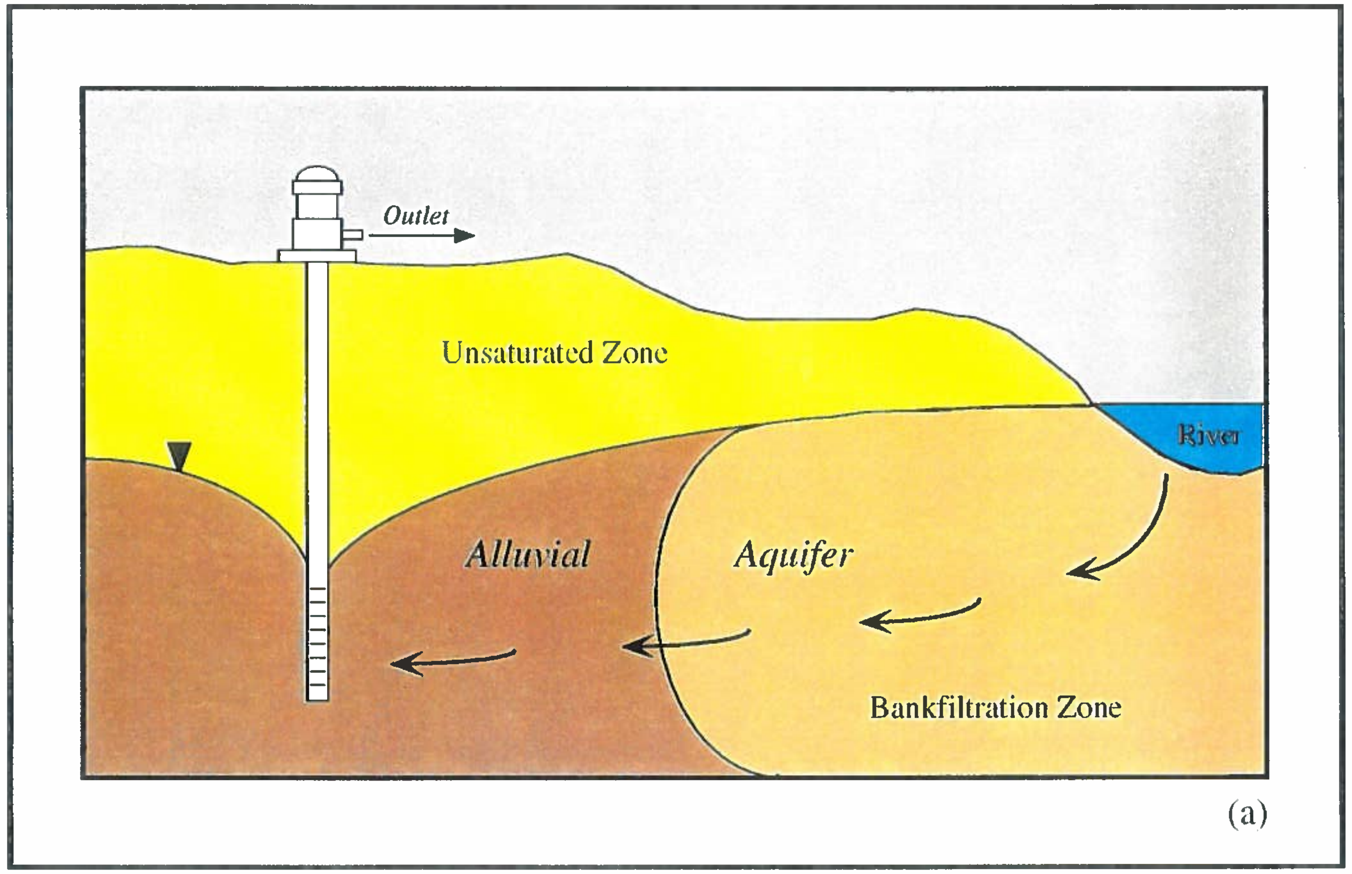

Figure 5.24a. Bankfiltration during induced infiltration from a river to a high-capacity well in a porous alluvial aquifer. Bankfiltration immobolizes and degrades many undesirable pollutants during transport from a contaminated river to the pumping well. This results in natural pre-treatment of poor quality river water.

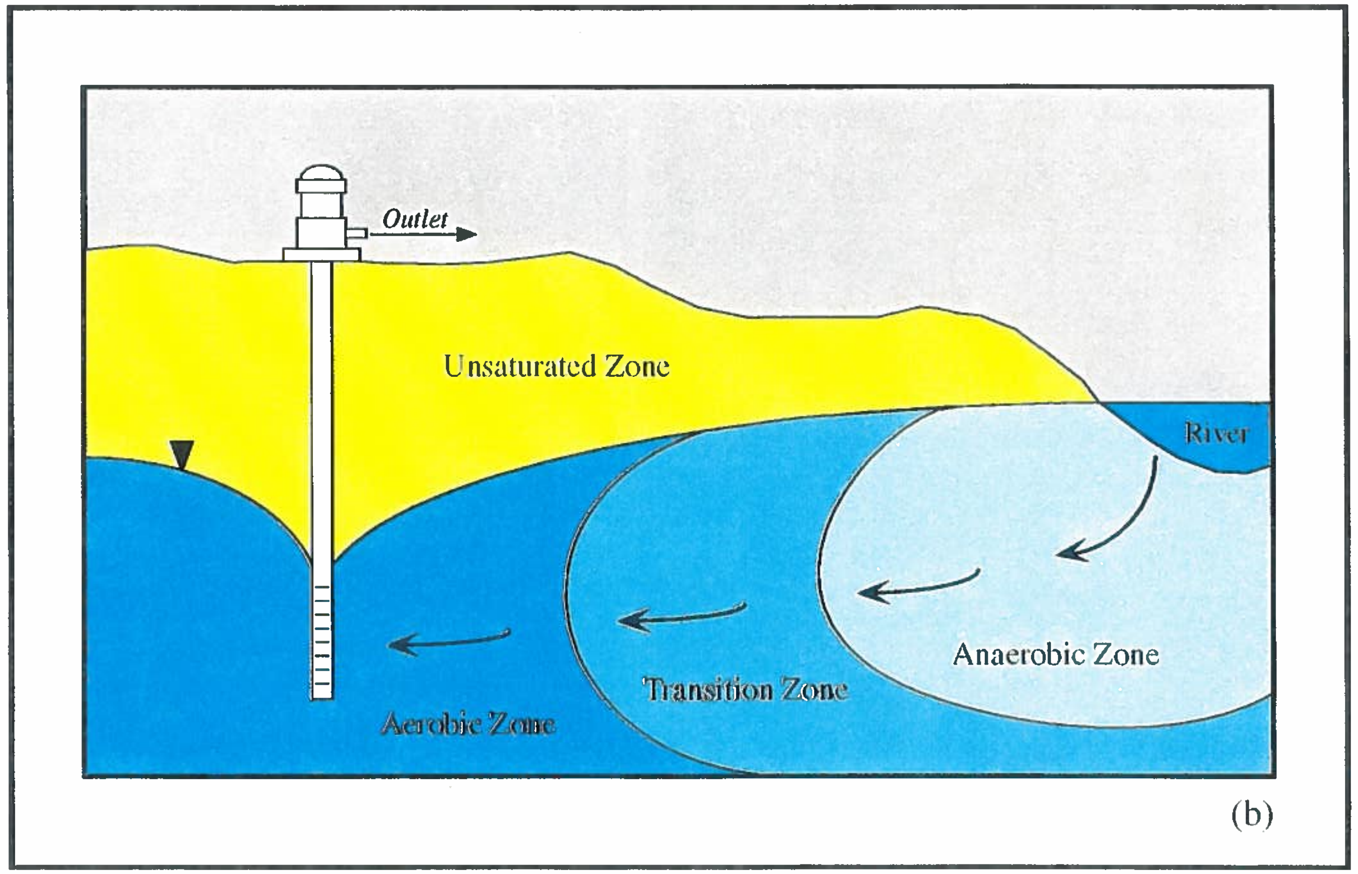

Figure 5.24b. Bankfiltration often creates redox zones as a result of microbial reduction of river micronutrients that have penetrated the aquifer during infiltration of river water. Close to the river, in the anaerobic zone, many metals and pollutants are mobile. In the aerobic zone, metals are fixed, and pesticides and organic pollutants may be biologically degraded.

Susceptibility to Contamination

The Rio Grande aquifer is highly susceptible to contamination. The aquifer can be contaminated rapidly by land application of fertilizers and pesticides, by leaching from septic tanks and feedlots, and by infiltration of chemicals or hazardous waste from storage facilities or from accidental spills. Consisting mostly of permeable unconsolidated deposits, the aquifer has received a DRASTIC index greater than 154 across much of the study area (Cross and Terry, 1991).

Where the Rio Grande aquifer is hydraulically connected to the Rio Grande, contaminants carried by the river can readily contaminate the aquifer. Contamination can occur due to (a) direct application of contaminated surface water, or by (b) induced infiltration of contaminated surface water (Figure 5.23). Rio Grande waters are already contaminated above the El Paso/Ciudad Juarez metroplex. Contaminants include TDS, fecal coliforms, sulfates, and chlorides (Eaton and Anderson, 1987). Possible causes of these contaminants include irrigation return flows, municipal discharges, and low flows in the fall and winter. The quality of Rio Grande water deteriorates further along and downstream of the City of El Paso/Ciudad Juarez corridor. Contamination is deduced by fecal bacteria as an indicator parameter. Immediately below El Paso, fecal coliforms as high as 290,500 colonies per 100 mL of water have been reported in Rio Grande water (Cech and Essman, 1992).

Induced infiltration occurs when drawdown from a high capacity well(s) reverses the hydraulic gradient between the well and the stream (Figure 5.24). The removal of suspended or dissolved substances in the infiltrated river water is called "bankfiltration." Bankfiltration may actually have a beneficial effect on drinking water supply and does not necessarily contaminate the aquifer. The process immobolizes and degrades undesirable pollutants by porous filtering, chemical attenuation, and biological decomposition during induced infiltration from a river to a high-capacity well (Figure 5.24). Even after many decades of well pumping, bankfiltration continues to remove more than 75 percent of the dissolved organic constituents in river water and as much as 95 percent of the heavy metals without substantial clogging (Sontheimer, 1980; Brand and others, 1989). In-situ pretreatment of heavily polluted river water by bankfiltration coupled with secondary (standard) water treatment usually ensures a high-quality drinking water supply.

Waters of very different chemistry and temperature mix during bankfiltration. The mixing gives rise to complex interactions between soils, bacteria, pollutants, and geochemical species. Organic micronutrients are concentrated in river water and settle in interstitial spaces in streambed and alluvial sediments during bankfiltration (Schwarzenbach and Westall, 1981; Brand and others, 1989). Microbial reduction of micronutrients often creates an anaerobic zone in the aquifer which remobilizes the pollutants (especially trace elements and heavy metals). The anaerobic zone is localized within a few tens of meters of the stream/aquifer interface (Brand and others, 1989). Beyond the anaerobic zone, the subsurface alluvial environment usually is first moderately, and then strongly, aerobic (Figure 5.24).

In the aerobic zones, trace elements and heavy metals are immobilized and many other pollutants are reduced to harmless chemical compounds. Weakly immobilized pollutants that have intruded into the aerobic zone may be remobilized (Brand and others, 1989). Nevertheless, a permanent aerobic zone is established at some distance from the stream/aquifer interface where redox conditions are perennially oxidizing and where water wells may be more safely located.

Future studies of the Rio Grande aquifer should identify aerobic zones where it is safer to install water wells. Water wells located too close to the river in the anaerobic zone may have higher yields, but may not derive the cleansing benefits of bankfiltration.

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CHAPTER 6 - DIABLO PLATEAU AQUIFER

Location and Extent

The Diablo Plateau covers all but the southern part of Hudspeth County, Texas (Figure 6.1). The plateau is juxtaposed against regional grabens that formed by Quaternary-age lateral extension and normal faulting. The Campogrande fault displaces Cretaceous strata against bolson deposits southwest of the fault, forming an escarpment of more than 400 ft (Fisher and Mullican, 1990). Together with Otero Mesa to the north, the Diablo Plateau is a gently eastward-sloping structure situated at an elevation of between 4,400 and 5,200 ft. It is bounded by the Hueco-Tularosa Bolson on the southwest, by the Steeruwitz Hills, Carrizo Mountains, Van Horn Mountains, and Wylie Mountains on the south and southeast, and by the Salt Basin and Otero Break on the northeast. The edge of the Sacramento Mountains define the northern boundary of the study area.

Stratigraphy and Water-Bearing Characteristics

In Texas the Diablo Plateau consists of two rock units: (1) the Permian carbonate and evaporite rocks of Leonardian and Guadalupian age in northern Hudspeth County and, (2) the Cretaceous carbonate and clastic rocks of the Finlay, Cox, and Campogrande Formations, which outcrop roughly south of the Dell City parallel. The primary water-bearing units over much of the Diablo Plateau are Permian rocks with an average thickness of 1,300 ft (Kreitler and others, 1987). Ground water is encountered at depths from 200 ft to 1,500 ft. In the Dell City area the Permian aquifer is locally known as the Victorio Peak-Bone Spring aquifer (Ashworth, 1995). Lithologic control for this aquifer outside the Dell City area is extremely limited.

The Cretaceous strata are reported to be at least 200 ft thick (Kreitler and others, 1987), and occupy the south-southwestern part of the study area. It is not yet known whether the Cretaceous strata in the Diablo Plateau are a unitary aquifer system, or if these rocks comprise several poorly connected aquifers (Fisher and Mullican, 1990).

In New Mexico, the plateau (known as the Otero Mesa) is composed almost entirely of Permian carbonate, clastic, and evaporite rocks of the Yeso, Victorio Peak, Bone Spring, and San Andres Formations (Mayer, 1995). Of these, only the Victorio Peak and Bone Spring Formations comprise the main aquifer. For convenience, the water bearing strata beneath the Diablo Plateau (Texas) and Otero Mesa (New Mexico) are grouped as the "Diablo Plateau aquifer." This aquifer includes the water bearing strata in the Dell City area. Diablo Plateau and Otero Mesa are terms used herein to describe separate physiographic provinces in Texas and New Mexico, not water bearing strata.

Aquifer tests conducted in the Diablo Plateau aquifer (Kreitler and others, 1987) suggest that permeabilities in the aquifer are solution-and-fracture controlled. Video logs run in several test holes revealed continuous vertical fractures and grapefruit-size dissolution cavities (Kreitler and others, 1990). Scalapino (1950) reports that only 44 percent of wells drilled in the Dell City area are prolific; many wells produce 100 gpm or less, even when drilled near wells successfully pumping 2,000 gpm. This response is an artifact of the high transmissivity contrast which characterizes the Permian and Cretaceous carbonate rocks in the Diablo Plateau region (Table 6.1).

Aquifer test data could not be located for the Otero Mesa region of New Mexico. Recent work by Mayer (1995) suggests that the transmissivity of Permian carbonate rocks in Otero Mesa is controlled by fracture density and orientation, and by local lithology. Mayer (1995) developed a ground water flow model for the region that provided transmissivity estimates ranging from 9.3 ft²/day to 9,300 ft²/day.

Potentiometric Surface Map and Water Levels

The potentiometric map for the Diablo Plateau aquifer and surrounding region indicates that ground-water flow is generally from southwest to northeast beneath the Diablo Plateau and from northwest to southeast beneath Otero Mesa (Figure 6.2). Flow from both regions converges towards Dell City and the Salt Basin along flowpaths with average hydraulic gradients of 0.0004 (Kreitler and others, 1987), although gradients are as steep as 0.001 (measured between wells 48-24-903 and 48-12-901). The Dell City area is encompassed by a shallow, broad cone of depression in the potentiometric surface that has formed as a result of extensive irrigation and ground-water development. A "trough" runs beneath the Sacramento River towards Dell City, its widely spaced contour lines suggesting high transmissivity along the trough. The potentiometric surface is near land surface in the Salt Basin where ground water discharges by evaporation.

The ground-water resources in the study region are mostly undeveloped, except in the Dell City irrigation district. Hydrographs of six wells in the Dell City area show significant changes in water levels since predevelopment (Figure 6.3). The rest of the system is almost at steady state. As pumping exceeded recharge, water levels dropped constantly until the mid-1980's at an average rate of 1.3 ft/year, totalling 25 to 45 ft of drop area-wide (Ashworth, 1995). Since then, irrigation pumpage diminished, and water levels have risen slightly (Figure 6.3).

Ground-Water Availability

Volumes of ground water in the Diablo Plateau/Otero Mesa proper cannot be estimated with available data due to very limited information on aquifer permeability and saturated thickness. In the Dell City area, Ashworth (1995) estimates that a sustained yield of 90,000 - 100,000 acre-ft/year may be derived in the irrigation district without additional drawdown.

Recharge Areas

Tritium and carbon-14 (^{14}C) levels measured in wells on the Diablo Plateau (Figure 6.4) indicate that most of the ground water samples contain recent water (i.e., water recharged within the last 50 years). The tritium and ^{14}C values display significant changes within short distances and no clear distribution pattern, thus emphasizing the practical importance of fracture and karstic flow. Recharge occurs over the entire plateau (approximately 2,900 mi²) as demonstrated by the areal distribution of tritium-rich samples (Figure 6.4). Most recharge probably takes place during flooding of the ephemeral creeks ("arroyos") that cross the plateau. Chloride profiles in soil water show lower chloride concentrations (less than 500 mg/L) in the creek soils and higher chloride concentrations (greater than 5,000 mg/L) in the inter-arroyo soils (Kreitler and others, 1990). This is indicative of significant recharge and flushing in the arroyos and smaller amounts of recharge in the interarroyo areas.

With calculated recharge rates of 0.0005 in/yr to 0.009 in/yr (Kreitler and others, 1987), the recharge rates over much of the plateau are perceptibly small. An exception is the Dell City irrigation district, which is estimated to receive about 31,000 acre-feet of non-irrigation recharge each year (Gates and others, 1980), mainly from the Sacramento River drainage basin (Young, 1976). The relatively high rates of recharge in this area imply higher local permeability, focused runoff, and rapid infiltration rates locally.

In the Otero Mesa area most of the recharge reaches the water table through creekbeds and depressions that temporarily store precipitation runoff. Mayer (1995) estimated a composite recharge rate of 0.007 in/yr over the 1,900 mi² occupied by the Otero Mesa. The Sacramento River ends about 45 miles northwest of Dell City, its flow captured by fractures and permeable sinks that replenish Otero Mesa locally.

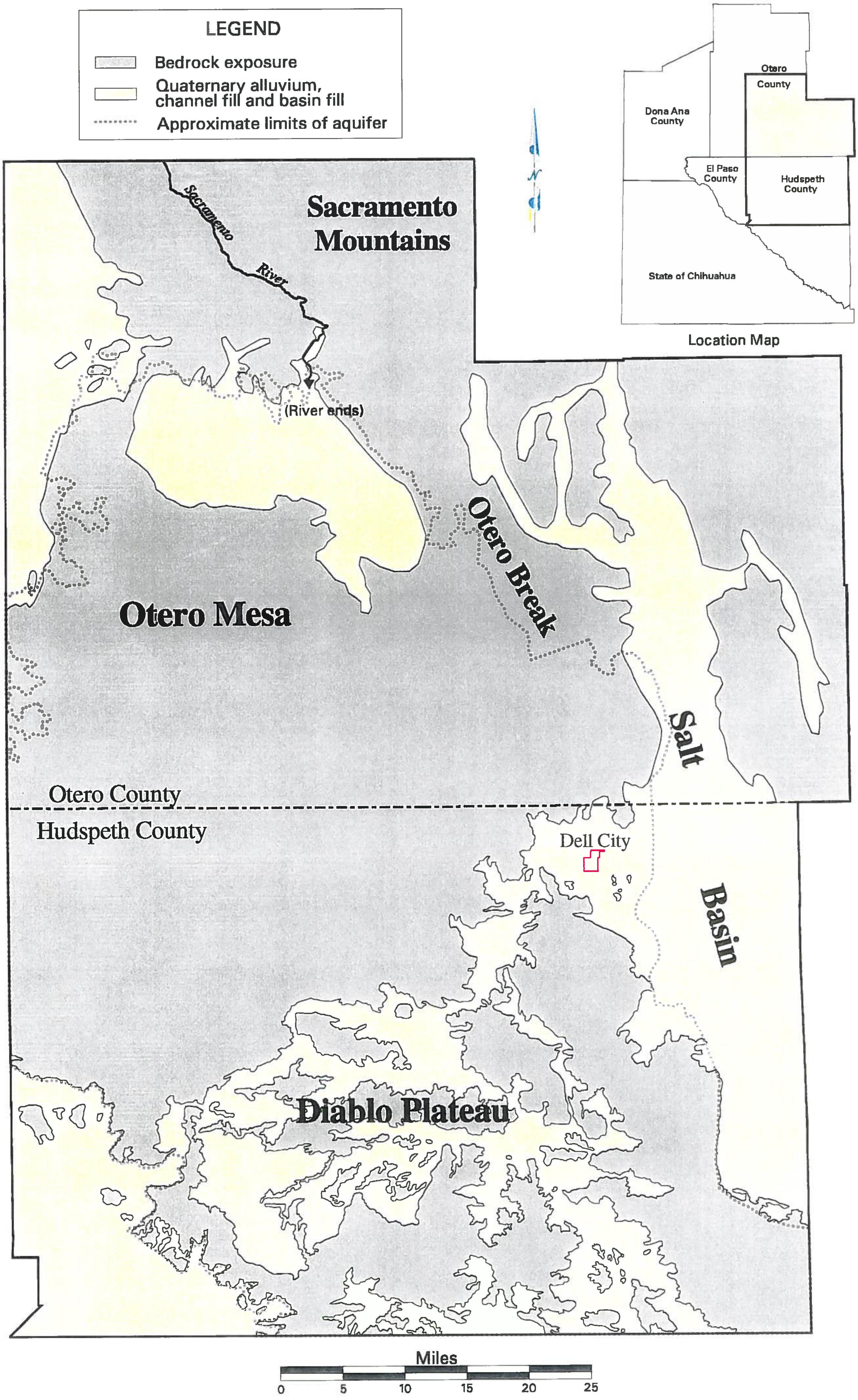

Figure 6.1. Location and extent of the Diablo Plateau aquifer and surrounding region.

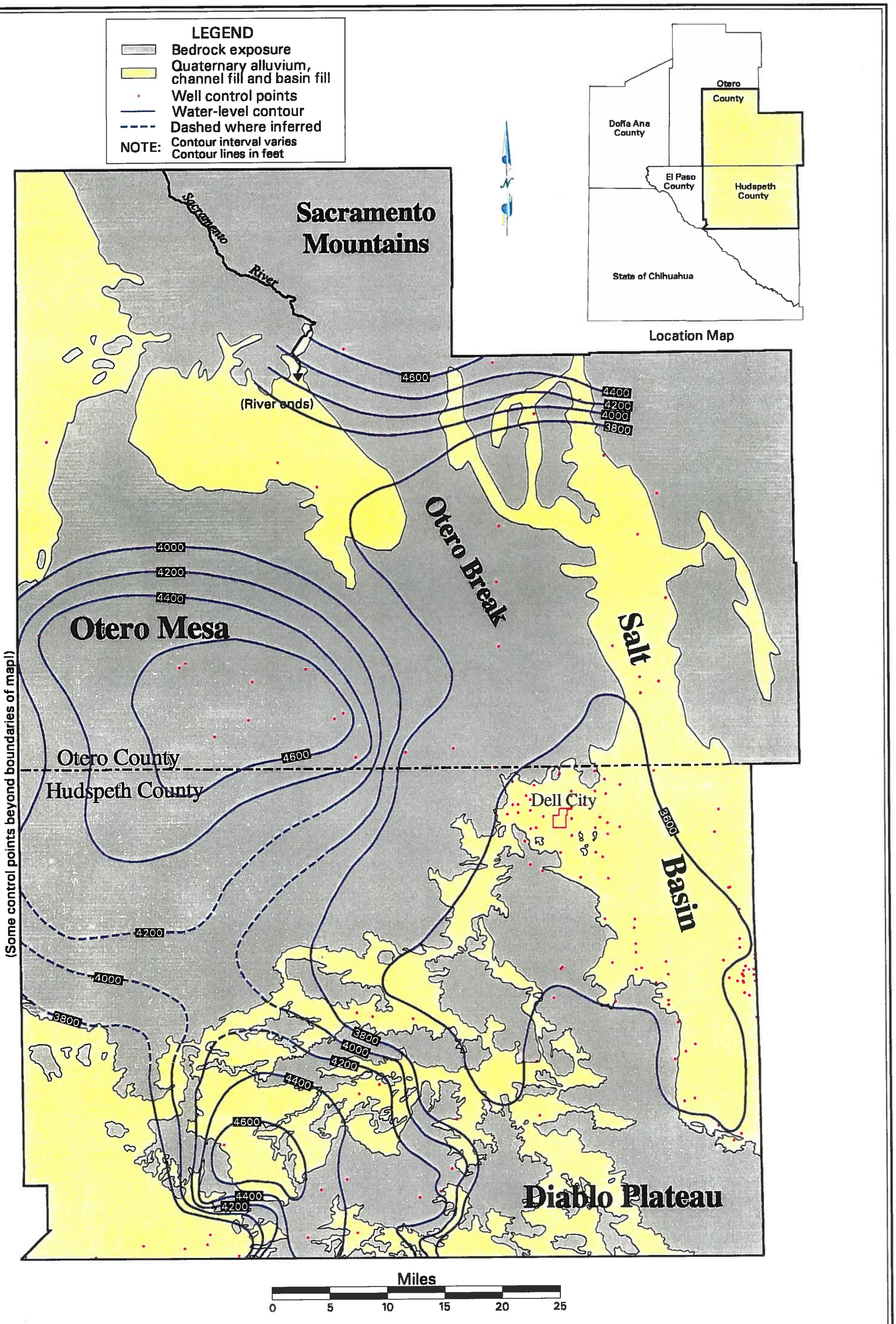

Figure 6.2. Regional potentiometric surface map for the Diablo Plateau aquifer and surrounding regions. Data for the Dell City area gathered in 1994. Other data in less developed and undeveloped areas gathered at various times. We assume quasi-steady state ground-water flow in undeveloped areas (source of data, Texas Water Development Board; Kreitler and others, 1986; Mayer, 1995).

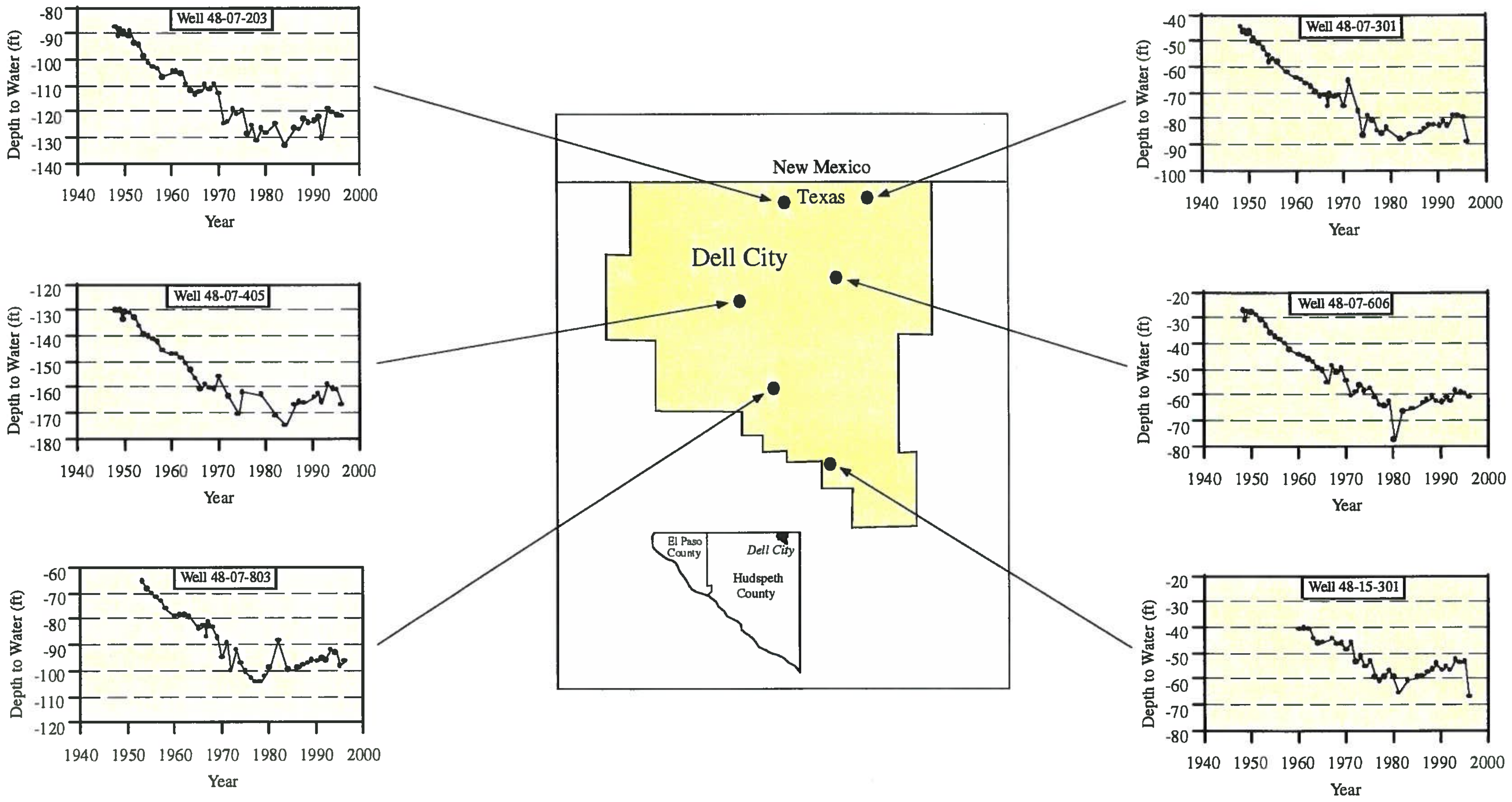

Figure 6.3. Hydrographs of selected wells in the Dell City area (modified from Ashworth, 1995).

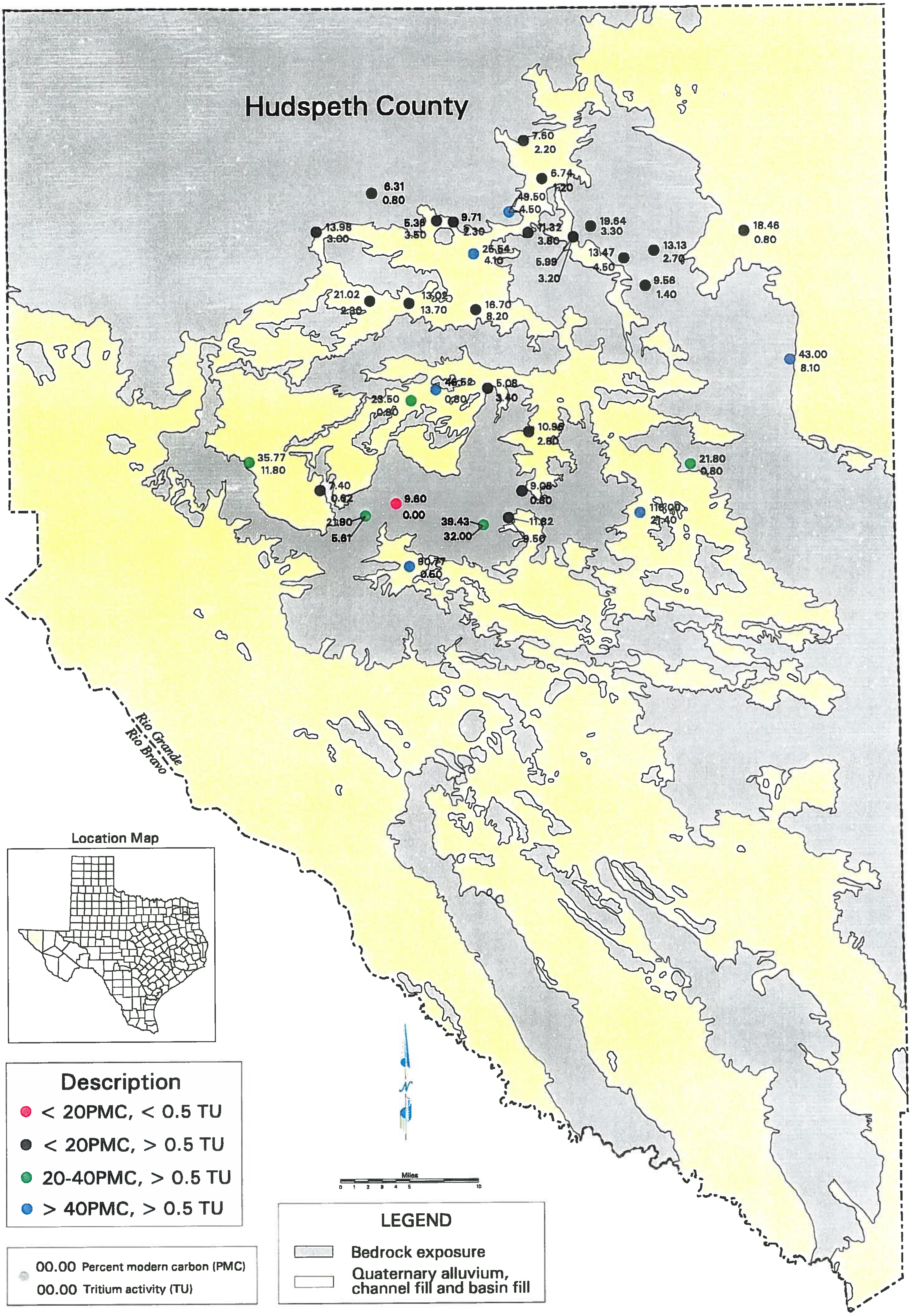

Figure 6.4. Map showing tritium activities (TU) and percent modern carbon (PMC) of ground water in the Texas portion of the Diablo Plateau aquifer (source of data, Kreitler and others, 1986).

Transmissivity Results From Aquifer Tests
In The Diablo Plateau Aquifer

State well number	Transmissivity (ft^2/day)	Water Bearing Strata
48-07-106	47,723.0	Permian
48-20-601	3.8	Permian
48-07-107	51,937.0	Permian
48-21-401	16.2	Permian
48-29-301	69.2	Permian
48-37-302	6,683.0	Cretaceous
48-39-101	0.5	Cretaceous

Table 6.1. Transmissivity values derived from aquifer tests in the Diablo Plateau aquifer (data from Logan, 1984; Kreitler and others, 1987).

Discharge Areas

Ground water in the Diablo Plateau aquifer is lost by discharge by irrigation wells, by ground-water evaporation, and possibly by interbasin ground-water flow (Figure 6.5). Before extensive irrigation began discharge also occurred through naturally flowing springs such as: Crow Springs, located east-northeast of Dell City; Washburn and Persimmon Springs north of Cornudas; Cove Spring on the southern side of the Paint Waterhole Mountains; Shot Springs in the Antelope Hills; Sulphur Springs on the east side of the salt flat; Cottonwood Springs southeast of the flat; and Aparejo (Harness) Springs on the southern side of Black Mountain (Brune, 1981).

Since 1958 about 85,000 acre-ft/yr has been pumped from the Dell City area for irrigating about 30,000 acres of cropland (Ashworth, 1995). Water levels in the aquifer have dropped and have eliminated most springflow (Figure 6.3). Natural discharge by evaporation occurs in the wet playas east of Dell City, as suggested by the shallow (3 ft) water table, thick capillary fringe, and upward hydraulic gradients in the salt flats (Kreitler and others, 1990).

Ground water from the Diablo Plateau aquifer may also discharge to the southeast at Balmorhea Springs and at the Cenozoic alluvial aquifer of Pecos County through interbasinal flow (LaFave and Sharp, 1987; Kreitler and others, 1990), although this hypothesis has not been proven (Figure 6.5). Permian carbonate units of the Diablo Plateau aquifer may be hydraulically connected to limestones beneath the Quaternary sediments of the Salt Basin. If permeability pathways exist in rocks beneath bolson sediments, ground water could travel along regional flowpaths to points of lower fluid potential at natural discharge areas southeast of the Diablo Plateau.

Water Quality

General hydrochemistry

Ground water in the Diablo Plateau aquifer is fresh to brackish, with total dissolved solids (TDS) concentrations as low as 500 mg/L in the Sacramento River area, to over 3,800 mg/L in central-western Otero Mesa where water-bearing strata are interbedded with the gypsiferous Yeso Formation (Plate 1). In the Dell City area, where return flow from irrigation leaches salts from the soils and evaporates, TDS concentrations reach 6,500 mg/L (Plate 1).

Hydrochemical facies in the area vary from Na-Ca-HCO_3 and Na-SO_4 in the southwest to Na-SO_4, Ca-SO_4, and Na-Cl in the north and northeast (Figure 6.6). The change in chemistry from southwest to north/northeast can be attributed to the changing lithology from Cretaceous carbonates to evaporate-rich Permian rocks along flowpaths, and to ground-water evaporation and mixing.

Origin of solutes

Prominent mineral dissolution and precipitation reactions that may control the hydrochemistries of the Diablo Plateau aquifer include:

Calcite dissolution and precipitation:

$$CaCO_3 + CO_2 + H_2O = Ca + 2HCO_3 \qquad (6.1)$$

Dolomite dissolution:

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O =$$

$$Ca + Mg + 4HCO_3 \qquad (6.2)$$

Gypsum dissolution:

$$CaSO_4 \bullet 2H_2O = Ca + SO_4 + 2H_2O \qquad (6.3)$$

Halite dissolution:

$$NaCl = Na + Cl \qquad (6.4)$$

and ion exchange:

$$Na_2\text{-clay} + Ca^{+2} = Ca\text{-clay} + 2Na^{+} \qquad (6.5)$$

$$Na_2\text{-clay} + Mg^{+2} = Mg\text{-clay} + 2Na^{+} \qquad (6.6)$$

Figure 6.7 shows the relationship between the concentration of (Ca + Mg) versus HCO_3 concentration. If all (Ca + Mg) were derived from calcite and dolomite dissolution, then data would plot along a line with a slope of 1:2, as stated by the calcite dissolution equation (6.1). Yet, all points are above the 1:2 line, thus indicating an additional source of Ca and Mg. A potential source of Ca is the Yeso Formation which contains gypsum (Mayer, 1995). To account for the Ca derived from gypsum dissolution, the SO_4 concentration is subtracted from (Ca + Mg), which is then plotted as a function of HCO_3 (Figure 6.8).

The majority of data points plot below the 1:2 line, indicating that although carbonate and gypsum dissolution explain much of the variations in Ca, Mg, and HCO_3 concentrations, another process, such as ion exchange between Ca and/or Mg and Na is removing Ca and/or Mg from solution. To test this hypothesis the concentration of (Na - Cl) is plotted against (Ca + Mg - SO_4 - 0.5HCO_3). The quantity (Na - Cl) represents "excess" Na; that is, Na coming from sources other than halite dissolution, assuming all Cl is derived from halite dissolution. The quantity (Ca + Mg - SO_4 - 0.5HCO_3) represents the Ca and/or Mg coming from sources other than gypsum and carbonate dissolution. These two quantities represent the maximum amount of Na and (Ca + Mg) available for ion exchange processes. The data (Figure 6.9) plot on a line with slope close to unity, suggesting cation exchange between Ca, Mg, and Na.

Figure 6.10 plots (Na/Cl) ratios versus Cl concentrations. Ratios of Na to Cl range from 0.3 to 4.0, and tend to approach unity with increasing chlorinity. Most of the Diablo Plateau/Otero Mesa samples show (Na/Cl) ratios greater than one due to ion exchange between dissolved Ca or Mg and adsorbed Na. Ratios less than one are common among the samples from the Dell City irrigation district and are attributed to a process of "reversed ion exchange", which occurs when dissolved Na is exchanged for bound Ca and Mg.

The water chemistry changes along flowpaths as ground water moves across the Diablo Plateau towards Dell City from a Na-mixed facies to a mostly Ca-SO_4 composition (Figure 6.11). These changes occurs as a result of gypsum dissolution and reversible ion exchange.

Isotopic analyses

Stable isotopes of hydrogen vs oxygen in ground water δ^2H versus δ^{18}O) cluster along the global meteoric water line (GMWL, Craig, 1961), pointing to a meteoric origin for ground waters of the Diablo Plateau aquifer (Figure 6.12). This assertion is strengthened by tritium data (Figure 6.4). The majority of samples have tritium, some of them up to 32 TU (Kreitler and others, 1986), indicating recharge of modern precipitation into the aquifers of the Diablo Plateau. Age determinations based on ^{14}C activities yielded ground-water ages from modern to 23,000 years old (Kreitler and others, 1986). Generally, the youngest waters, which also show the highest tritium activities occur in the southwestern part of the plateau while the older waters with less tritium are encountered towards the northeast (Figure 6.4). Some waters also display higher tritium activities accompanied by low percentages of modern carbon (PMC). This combination suggests mixing between old ground waters and modern ground waters.

Historical change

Except for the Dell City area, the ground water resources in the Diablo Plateau aquifer are largely undeveloped. It is assumed here that the only changes with time in ground-water chemistry occurred in the

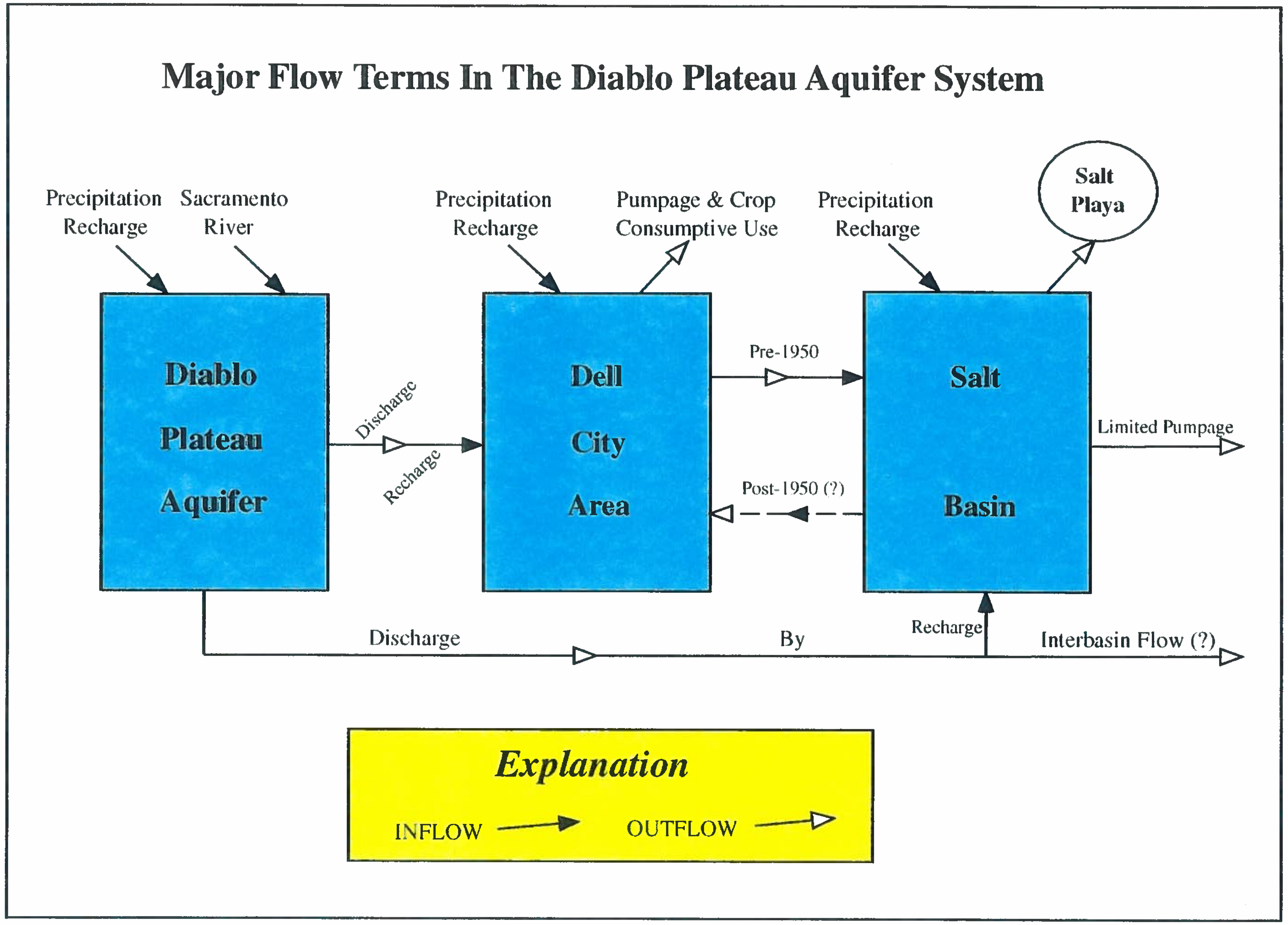

Figure 6.5. Major flow terms in the Diablo Plateau aquifer system.

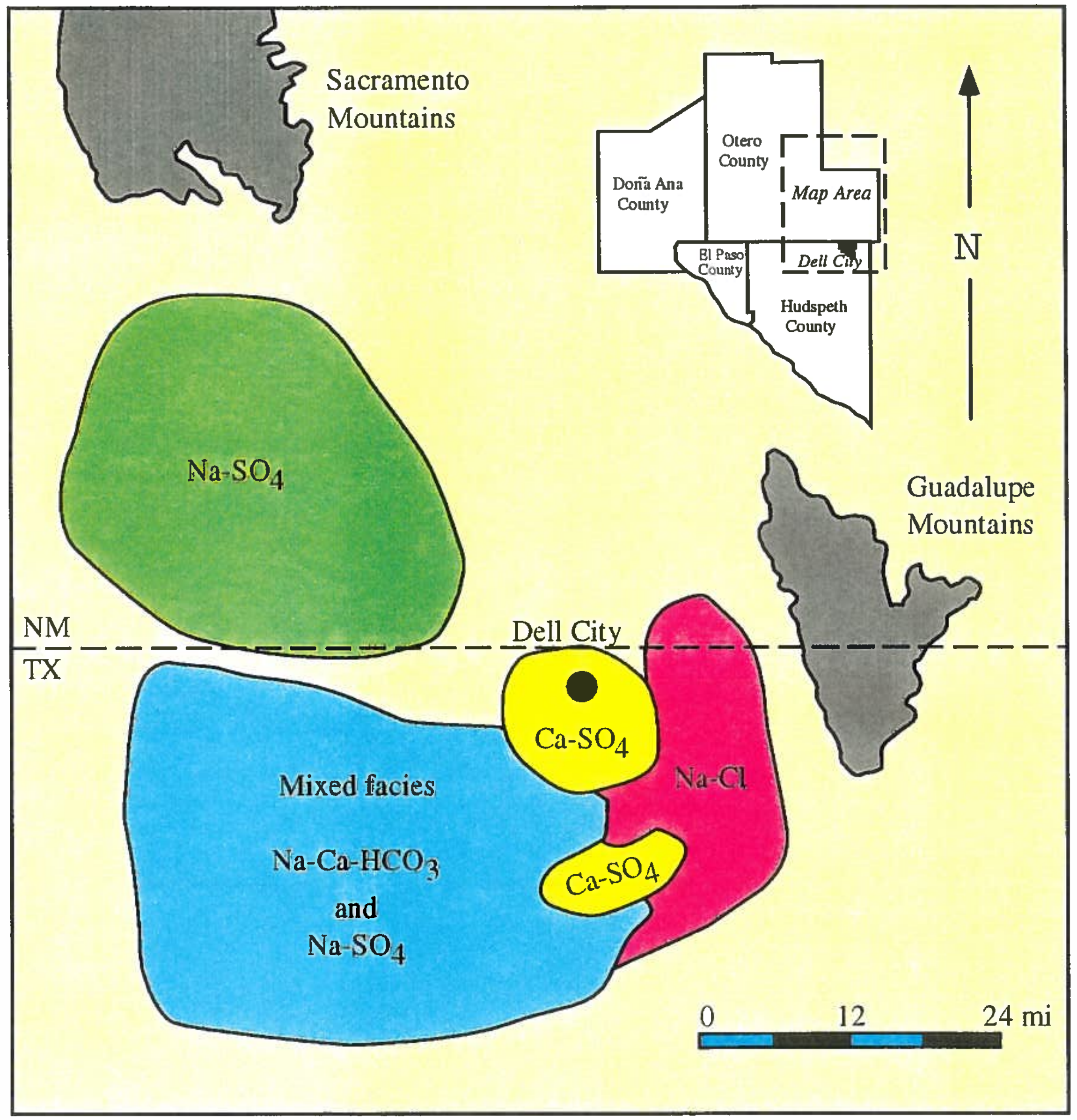

Figure 6.6. Areal distribution of ground-water facies in parts of the Texas and New Mexico portions of the Diablo Plateau aquifer (source of data, Texas Water Development Board; Kreitler and others, 1986; Mayer, 1995).

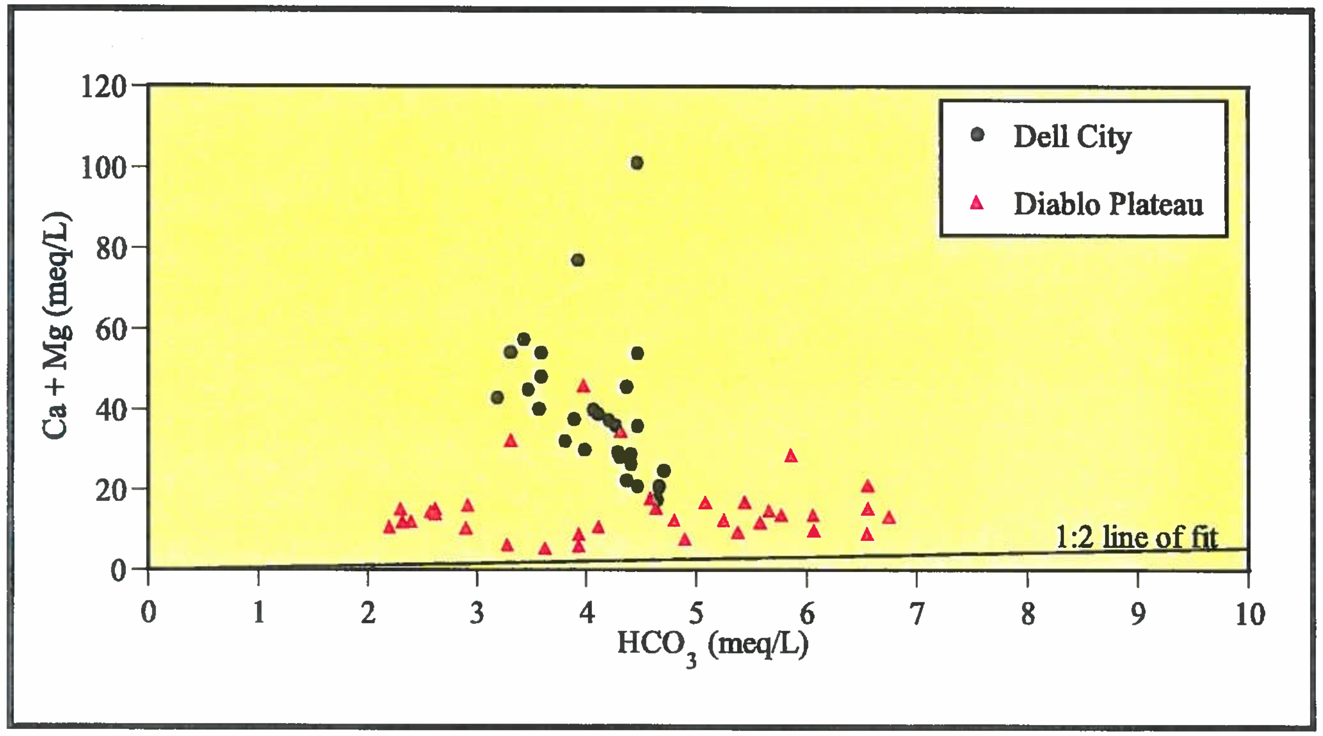

Figure 6.7. Plot of (Ca + Mg) vs HCO₃ .

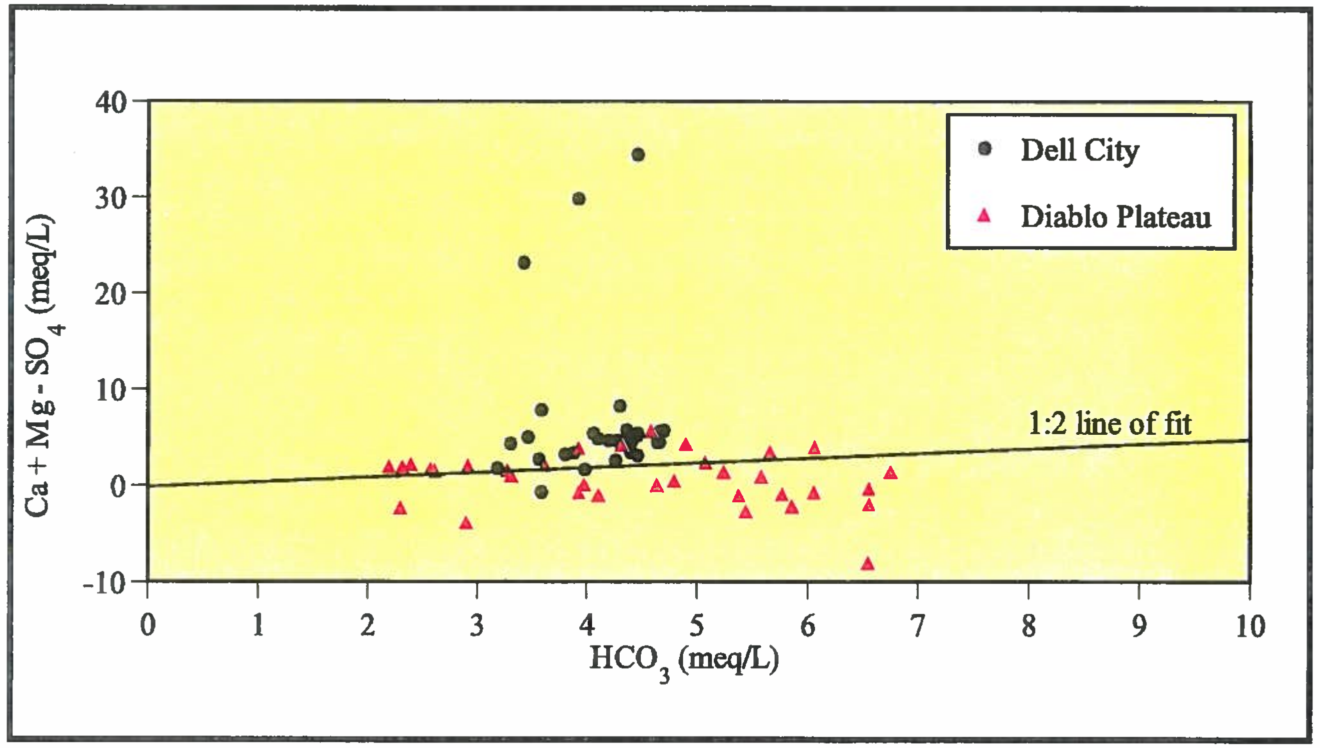

Figure 6.8. Plot of (Ca + Mg - SO₄) vs HCO₃.

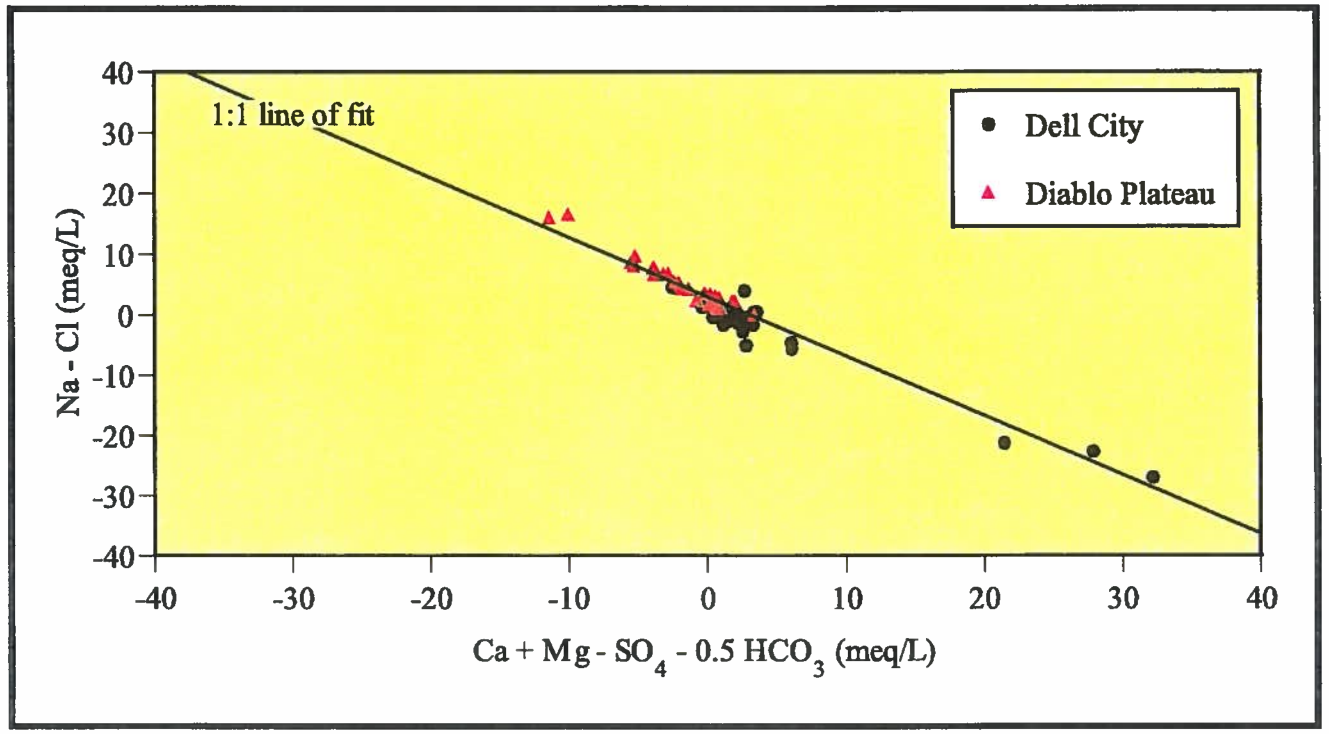

Figure 6.9. Plot of (Na - Cl) vs (Ca + Mg - SO₄ - 0.5HCO₃).

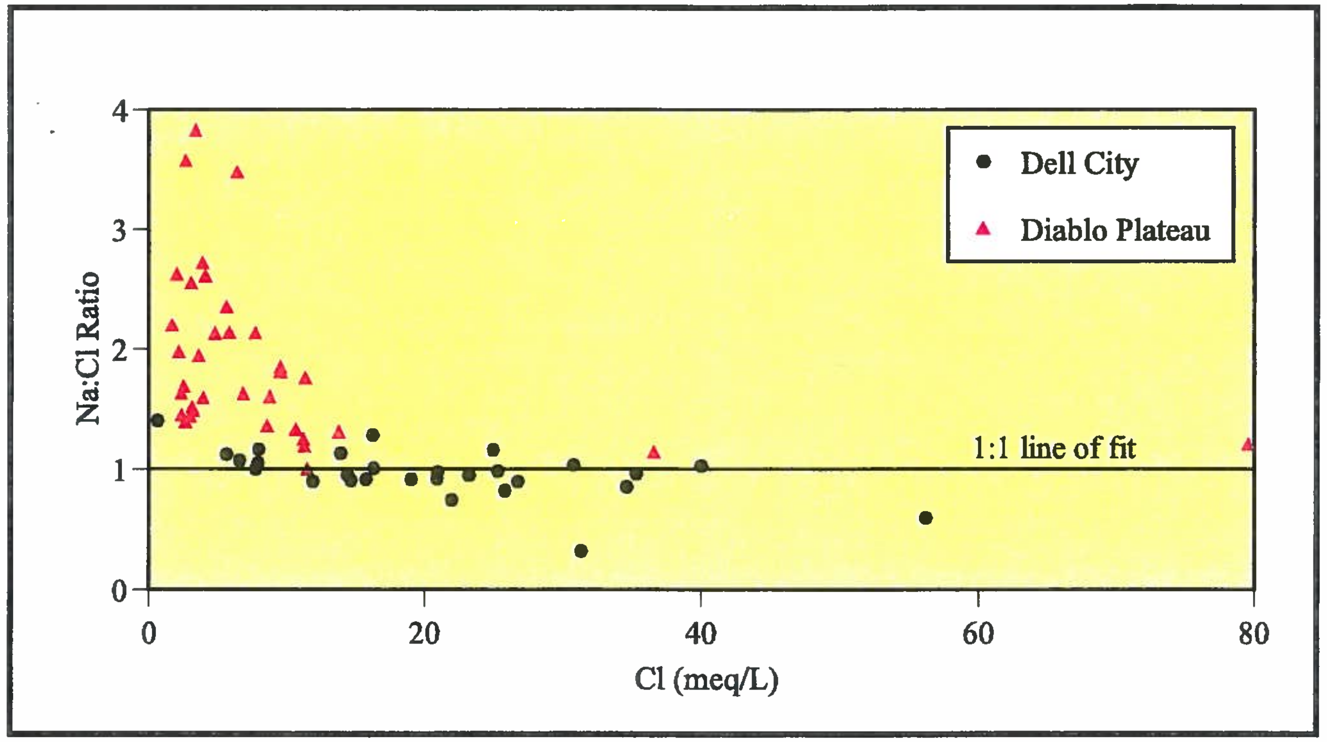

Figure 6.10. Plot of (Na/Cl) ratio vs Cl.

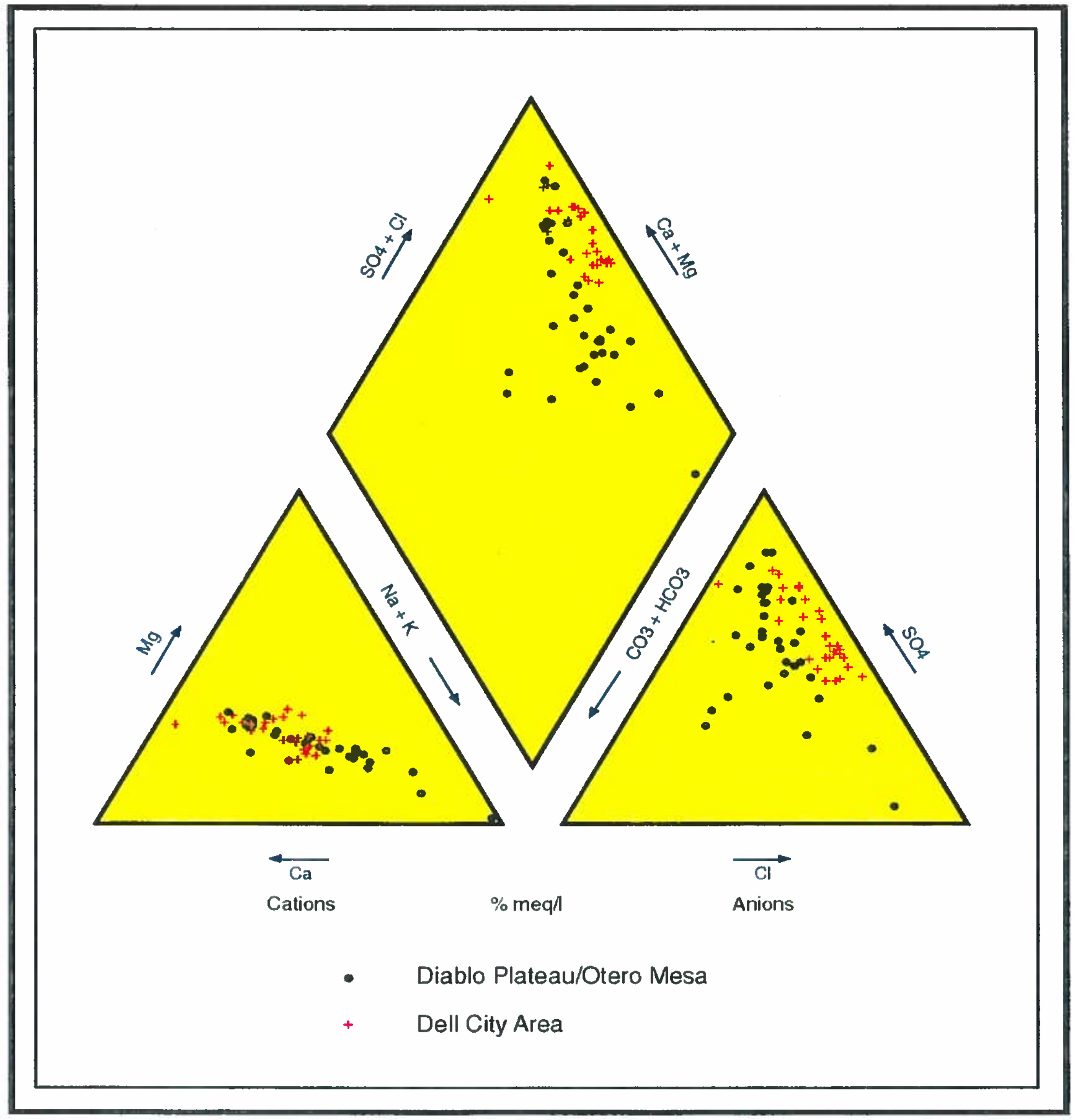

Figure 6.11. Piper diagram illustrating geochemical types for ground water in the Diablo Plateau aquifer (source of data, Texas Water Development Board; Kreitler and others, 1986; Mayer, 1995).

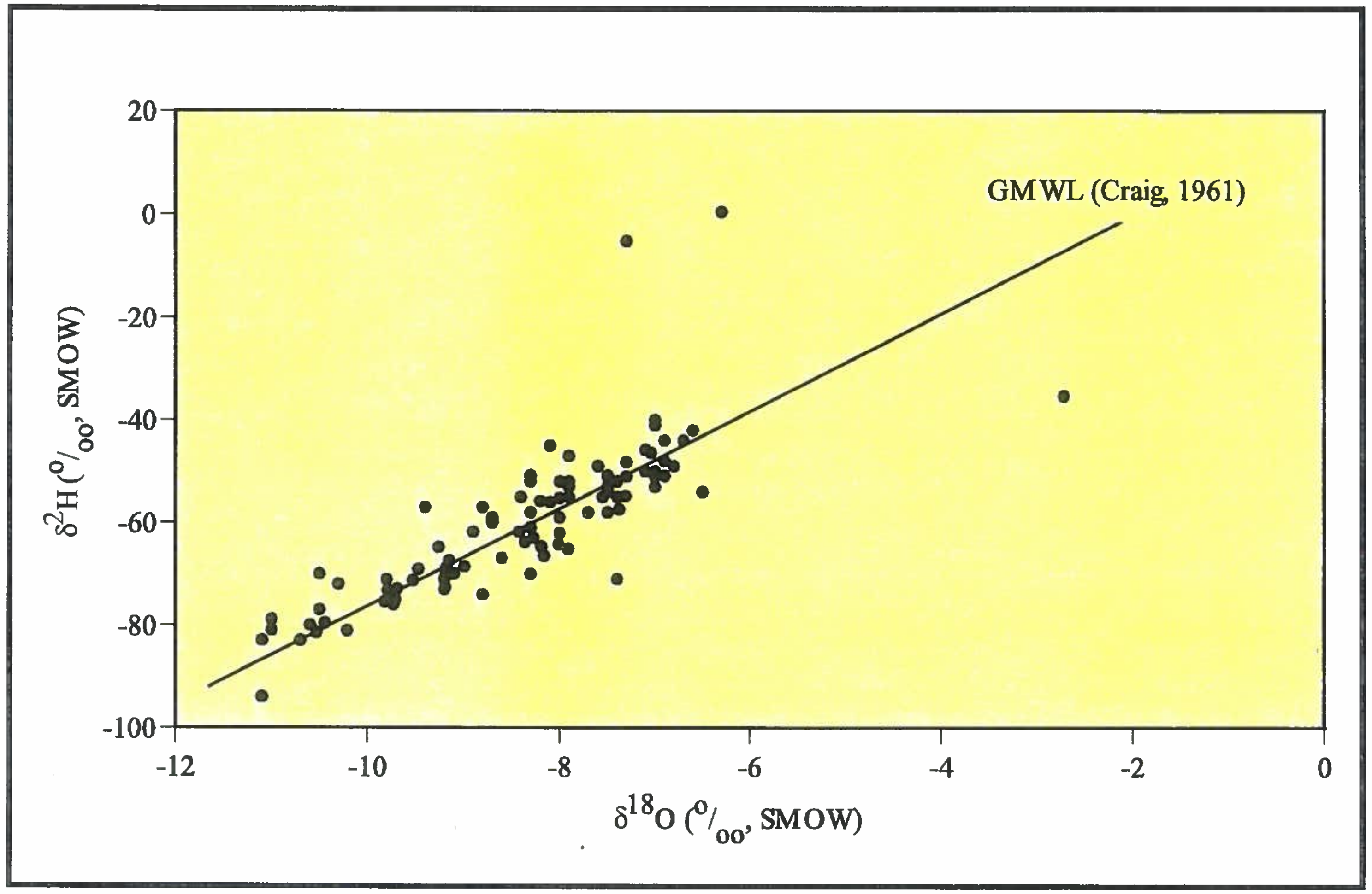

Figure 6.12. Plot of δ^2H vs $\delta^{18}O$ (source of data, Kreitler and others, 1986).

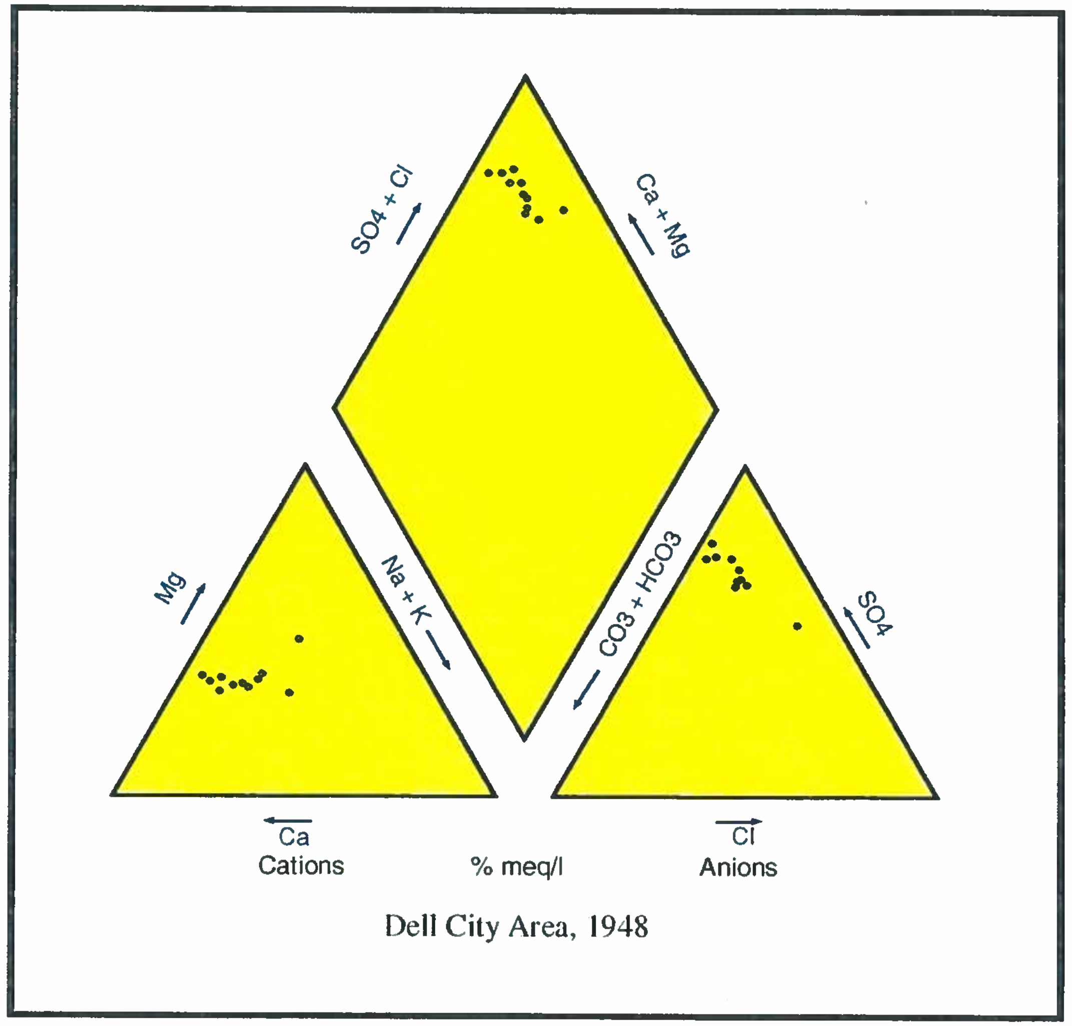

Figure 6.13a. Chemical composition of Dell City ground water in 1948 (source of data, Texas Water Development Board).

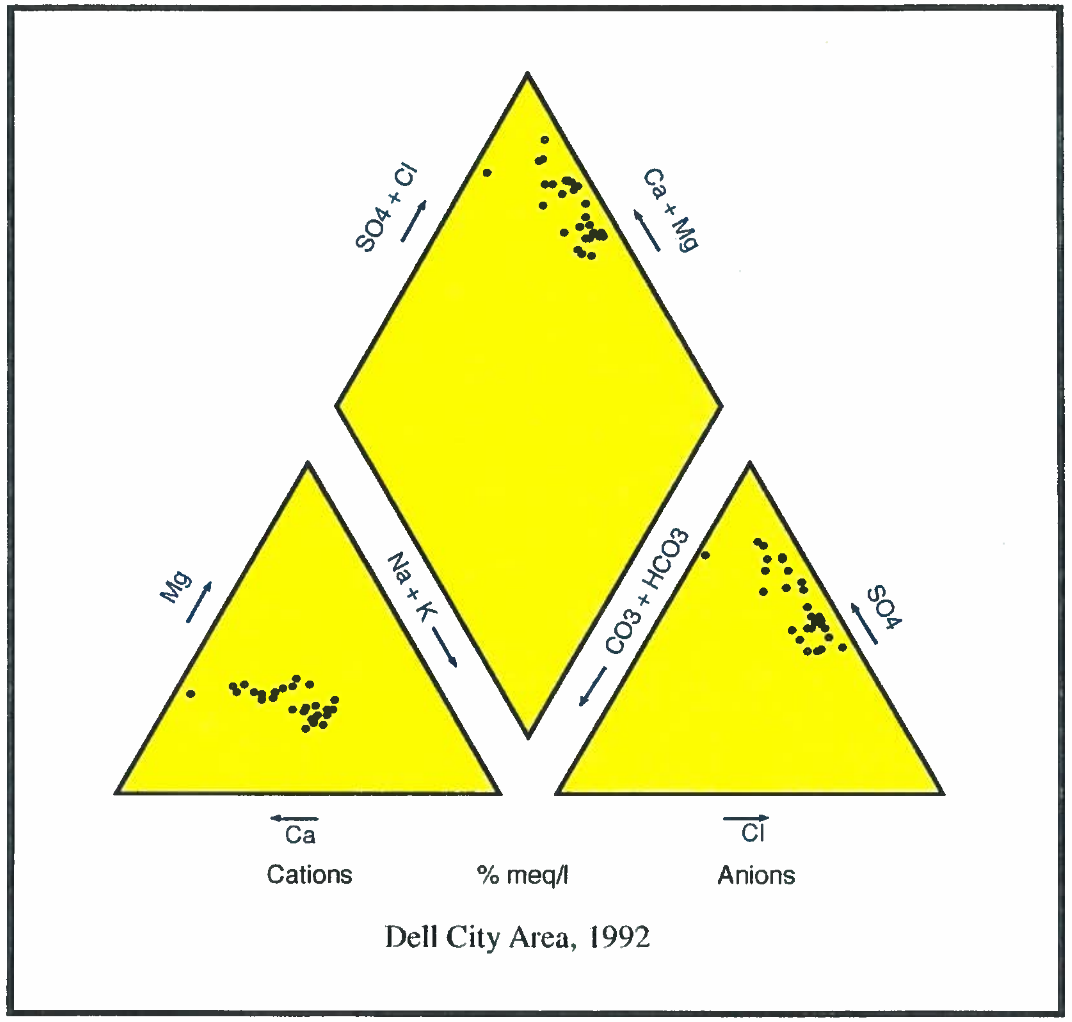

Figure 6.13b. Chemical composition of Dell City ground water in 1992 (source of data, Texas Water Development Board).

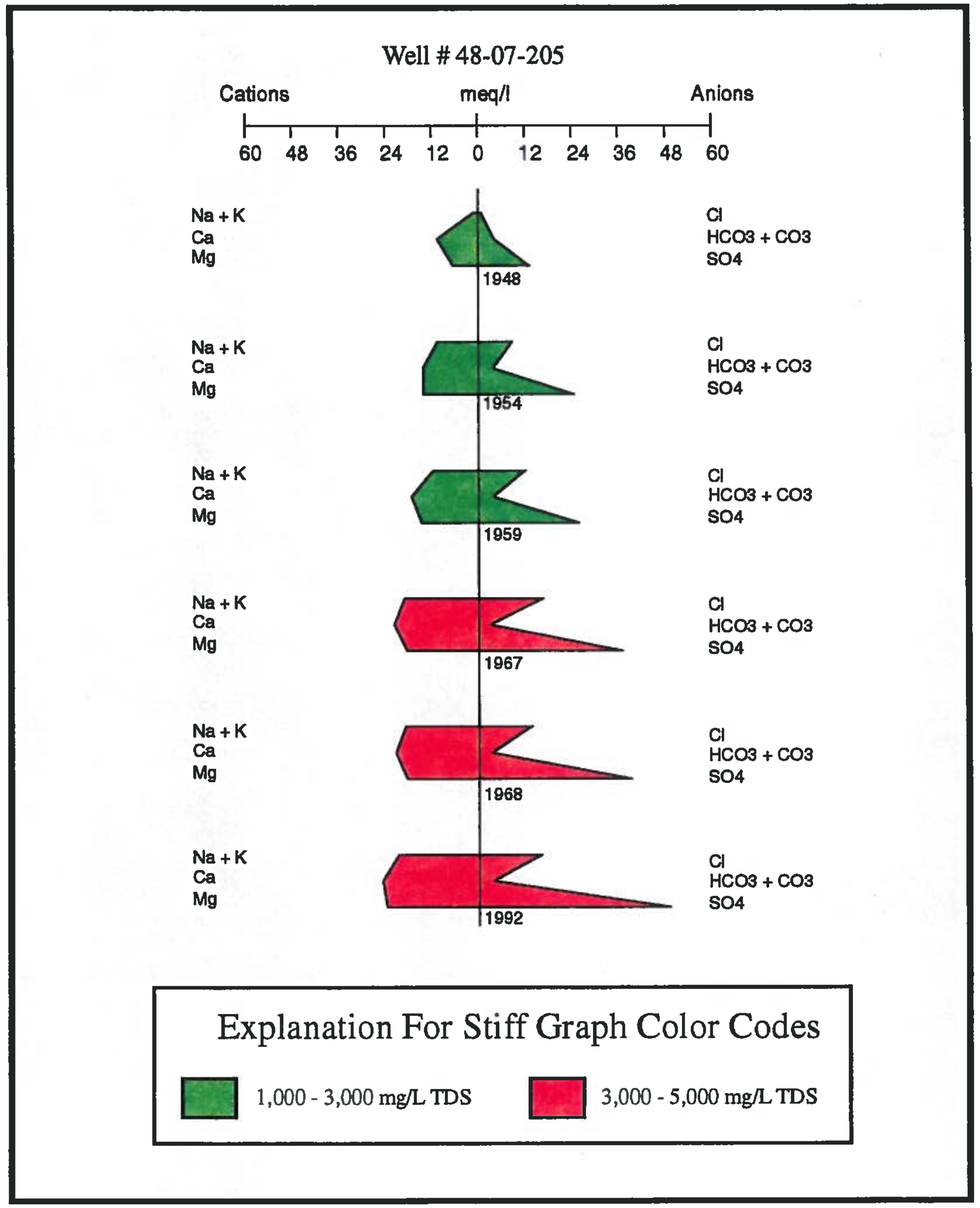

Figure 6.14a. Stiff diagram showing major ion chemistry changes through time in well 48-07-205 (source of data, Texas Water Development Board).

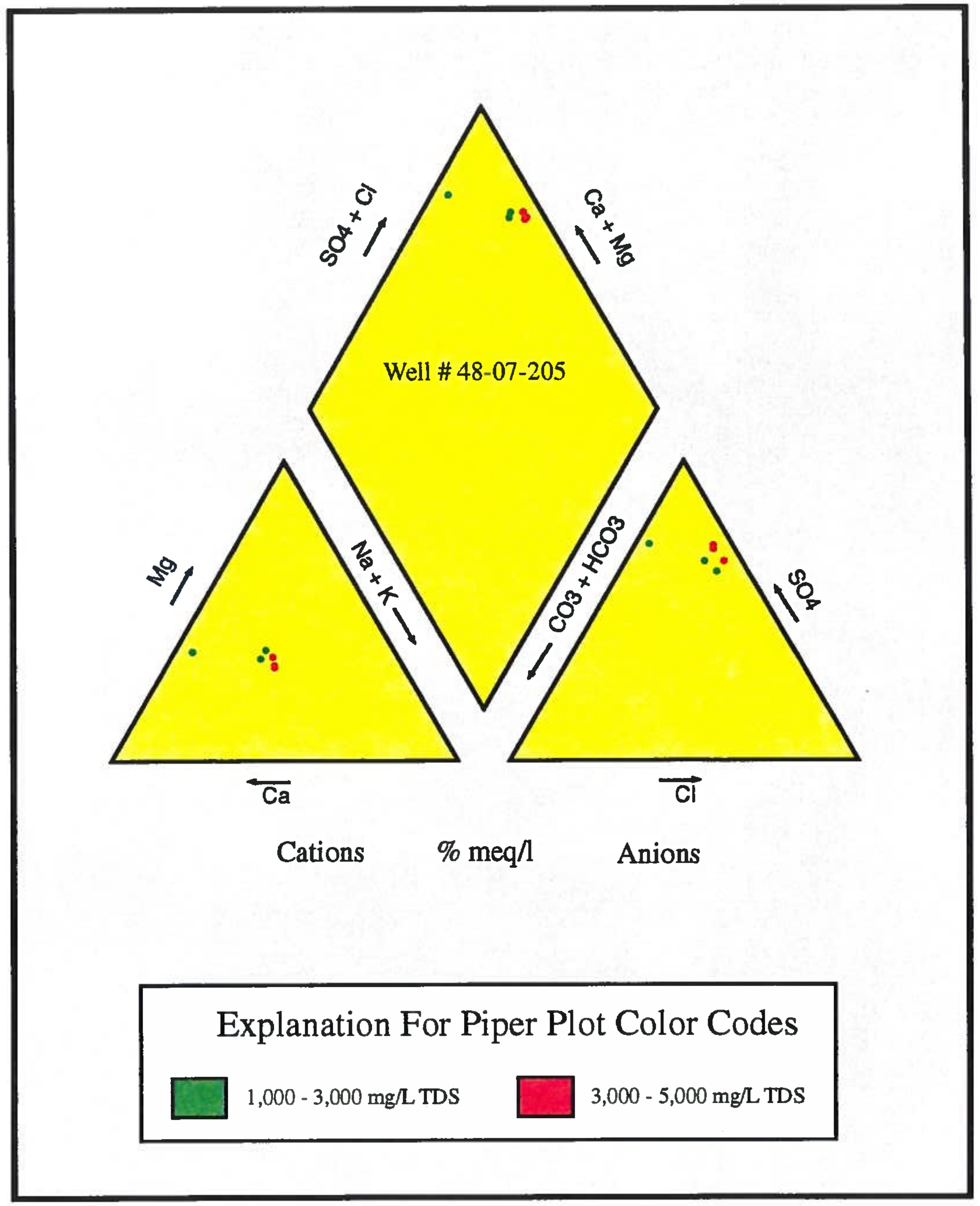

Figure 6.14b. Piper diagram showing major ion chemistry changes in well 48-07-205, also represented in Figure 6.14a (source of data, Texas Water Development Board).

Dell City irrigation district, and the rest of the flow system is fairly stable with respect to dissolved solutes.

Figure 6.13 shows Piper diagrams for 1948 and 1992 ground-water chemistry in Dell City irrigation wells. Data indicate an overall shift from a $Ca\text{-}SO_4$ type in 1948 to a $Ca\text{-}Na\text{-}SO_4\text{-}Cl$ type in 1992. Changes in water chemistry through time in irrigation well 48-07-205 are shown in Figure 6.14. The major trends identifiable on the Stiff diagram are a pronounced increase in sulfate, chloride, and sodium concentrations, moderate increases in calcium and magnesium, coupled with a decrease in bicarbonate ion concentration. Overall, this translates into a steady salinization of water from this well by as much as 3,500 mg/L total dissolved solids.

To account for the temporal change in calcium, magnesium, bicarbonate, and sulfate, the following model could be employed (Mayer, 1995): gypsum dissolution causes an increase in sulfate and calcium ions concentration, followed by calcite oversaturation and precipitation (Mayer, 1995). The loss of carbonate ions leads to dedolomitization (Back and others, 1983), and to the solution of magnesium. In this light, increases in chloride and sodium ions concentrations could be explained by either halite dissolution, or mixing with an evaporative brine, such as irrigation return flow.

Susceptibility to Contamination

The Diablo Plataeu aquifer is moderately susceptible to contamination. The Diablo Plateau has a moderate ground-water pollution potential (DRASTIC index) that ranges from 95 - 124 for agricultural sources (TWC, 1989), the principal activity in the region. The DRASTIC index for general, municipal, and industrial sources ranges from 80 - 124 (TWC, 1989).

High tritium activities in most of the samples collected from the Diablo Plateau aquifer, along with stable isotope signatures that indicate a meteoric component of recharge provide uncompromising evidence of precipitation recharge to the Diablo Plateau aquifer. The recharge rate is not high however and the bulk ground-water ages, identified by ^{14}C, are generally old. The isotope data suggest that any contaminants carried by infiltrating rainwaters to the saturated zone may be diluted by copious quantities of much older ground water.

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RECOMMENDATIONS

In establishing the Transboundary Aquifer GIS coverages and binational aquifer maps, a significant amount of data was acquired, verified, and evaluated. The value of any coverage or map is dependent on there being a sufficient amount of data to adequately and accurately characterize the subject matter. 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.

- Recharge to and contamination susceptibility of aquifers are significantly influenced by the geology of an area. The geology of the Texas portion of the project area is currently being refined by the BEG. Revisions of existing maps should be digitized as replacements for the existing geology coverage. Mexico geology (Figure 1.5) should be more accurately and completely digitized.

- The extent of the Conejos Medanos (Mesilla) aquifer in Mexico should be better delineated and digitized. Hydrogeologic data from this aquifer is needed for addition to its extent in New Mexico and Texas.

- 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.

- Specifically, potentiometric surface maps and hydrographs for the Mexican portion of the Rio Grande aquifer should be added to maps prepared in this report for the U.S. part of the aquifer. The absence of well elevations in Mexico precluded the preparation of binational maps for the Rio Grande aquifer.

- The proliferation of colonias on the Rio Grande alluvial floodplain, many of which are without adequate water and wastewater facilities, may have intensified contamination of the shallow aquifer by untreated or poorly treated sewerage. Effects of development on water quality should be monitored and evaluated for potential problems.

- 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 Mexican part of the Hueco Bolson are not well known and are very difficult or impossible to estimate with available data. Further studies should be conducted to derive better stratigraphic data and better estimates of recoverable ground water in storage.

- Quantification of recharge potential, similar to the process developed by the NMWRRI, should be applied in Texas and Mexico.

- Computer ground-water flow models of the Hueco Bolson aquifer currently being developed by Mexico and the U.S. should be supported. The same binational modeling effort should be made at a later date for the Mesilla/Conejos Medanos aquifer.

- Radioisotope data is needed to determine ground-water ages, ground-water residence times, recharge areas, and areas of cross-formational flow. The quality of the ground-water flow models being developed by the USGS and Mexican government will improve if isotope data is available.

- 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 Juarez employ pumping schemes for reduced salinity.

- Mexican well data generated prior to about 1990 was available only in hard copy. This data should be converted to electronic files.

- A formal procedure and timetable for binational ground-water data exchange should be reestablished. 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.

- 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 Mexican portion of the transboundary aquifers, and to seek technical solutions to common ground-water problems.

- 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.

APPENDIX A

List of Water-Related Agencies and Institutions

Border Environmental Cooperation Commission
Blvd. Tomas Fernandez No. 7940, Torres Campestre
Piso 6o.
Cd. Juarez, Chihuahua
Mexico C.P. 32470
Phone: (52-16) 29-23-95; 29-23-95; Fax: 29-23-97; 29-23-97

Comision Internacional de Limites y Aguas
Seccion Mexicana
Av. Universidad 2180
Zona del Chamizal
Cd. Juarez, Chihuahua, 32310
Telephono: 13-99-42

Comision Nacional Del Aqua
Texcoco 4860
Ciudad Juarez, Chihuahua 32310
Telephono: 13-77-16

El Paso Water Utilities Public Service Board
P. O. Box 511
El Paso, TX 79961
Phone: (915) 594-5562; Fax: 594-5699

International Boundary & Water Commission
Mexican Section
P.O. Box 10525
El Paso, TX 79995

International Boundary & Water Commission
United States Section
4171 N. Mesa, C-310
El Paso, TX 79902
Phone: (915) 534-6700; Fax: 534-6680

Junta Municipal de Aqua y Saneamiento
Ave. Eje Juan Gabriel y Pedro N. Garcia
Ciudad Juarez, Chihuahua, CP 32380
Telephono: 16-06-73

New Mexico State Engineer Office
133 Wyatt Drive, Suite 3
Las Cruces, NM 88005
Phone: (505) 524-6161

New Mexico State University
Water Resources Research Institute
Box 3Z
Las Cruces, NM 88003
Phone: (505) 646-4337; Fax: 646-6418

Institutio Nacional de Ecologia
SEDESOL
Calle 9 #9, Col. Ignacio Zaragoza
Mexico D.F.
Mexico C.P. 15000
Phone: (52-5) 553-1235; Fax: 286-7971

Texas General Land Office
Stephen F. Austin Building
1700 N. Congress Avenue
Austin, TX 78701-5001
Phone: (512) 463-5001; Fax: 475-1415

Texas Natural Resource Conservation Commission
Region 6 -Field Operations Division
7500 Viscount Blvd., Suite 147
El Paso, TX 79925
Phone: (915) 778-9634; Fax: 778-4576

Texas Natural Resource Conservation Commission
Ground-Water Assessments Section
P. O. Box 13087; MC 147
Austin, TX 78711
Phone: (512) 239-4514; Fax: 239-4450

Texas Parks & Wildlife Department
Resource Protection Division
4200 Smith School Road
Austin, TX 78744
Phone: (512) 389-8014; Fax: 389-4394

Texas Water Development Board
Water Supplies Section
P. O. Box 13231 Capitol Station
Austin, TX 78711
Phone: (512) 936-0881; Fax: 936-0889

Texas Water Development Board
Hydrologic Monitoring Section
P. O. Box 13231 Capitol Station
Austin, TX 78711
Phone: (512) 936-083; Fax: 936-0831

Texas Natural Resources Information System
Borderlands Data and Information Center
Texas Water Development Board
P. O. Box 13231 Capitol Station
Austin, TX 78711
Phone: (512) 463-8337; Fax: 463-7274

United States Department of Agriculture
Natural Resources Conservation Service
11930 Vista del Sol, Suite B
El Paso, TX 79936
Phone: (915) 855-0884; Fax: 855-0936

United States Department of Interior
Bureau of Reclamation
Rio Grande Project Office
700 E. San Antonio, Suite 318
El Paso, TX 79901
Phone: (915) 534-6324; Fax: 534-6299

United States Department of Interior
Geological Survey
P. O. Box 30001, Dept. 3ARP
New Mexico State University
Las Cruces, NM 88003-0001
Phone: (505) 646-1335; Fax: 646-7949

United States Environmental Protection Agency
Region 6, Office of Ground Water
1445 Ross Avenue
Dallas, TX 75202-2733
(Need Phone & Fax Number)

United States Environmental Protection Agency
EPA Border Liaison Facility
4150 Rio Bravo, Suite 115
El Paso, TX 79902
Phone: (915) 533-7273; Fax: 533-2327

University of Texas at El Paso
Center for Environmental Resource Management
P. O. Box 646
El Paso, TX 79968
Phone: (375) 747-5494; Fax: 747-5145

University of Texas at El Paso
Department of Geological Sciences
Geology Building 223
El Paso, TX 79968
Phone: (915) 747-5593; Fax: 747-5073

APPENDIX B

List of Public Presentations, Articles, and Abstracts Given as Part of the EPA-Sponsored Transboundary Aquifer Study.

Texas Team Participants

Public Presentations

Ground water studies in the Rio Grande region, presented by Radu Boghici to the Symposium on Data Availability in the Texas/Mexico Borderlands, sponsored by the Texas/Mexico Borderlands Information Center and the Center for Environmental Resources Management, LBJ School of Public Affairs, June 12, 1997, Austin, Texas.

Interbasin ground-water flow in the Trans-Pecos region of westernmost Texas, presented by Barry Hibbs to the Department of Geological Sciences, University of Texas at El Paso, November 5, 1996, El Paso, Texas.

Geologic and hydrologic framework of the Hueco Bolson, presented by John Ashworth to the Binational Water Program Forum, University of Texas at El Paso, Shared groundwater, the Hueco Bolson: Binational needs and responsibilities, May 7, 1996, El Paso, Texas.

New emphasis on Transboundary Water Resources, presented by John Ashworth to the American Water Resources Association annual symposium, November 8, 1995, Houston, Texas.

Articles

Hibbs, B.J., and Boghici, R., 1997, in press, Saltwater encroachment along the City of El Paso/Ciudad Juarez corridor: in Long Beach '97, Annual Conference and Symposium on Conjunctive Use of Water Resources, Aquifer Storage and Recover, American Water Resources Association, 11 p.

Hibbs, B.J., Darling, B.K., Ashworth, J.B., and Sharp, J.M., 1996, Simulation of regional ground-water flow on a transboundary flowline, Trans-Pecos, Texas and Chihuahua, Mexico: in Chenchayya, T., and Bathala, F., eds., Destructive Water, North American Water and Environment Congress, New York, American Society of Civil Engineers, CD-ROM, 8 p.

Hibbs, B.J., and Jones, I.C., 1996, Hydrogeologic and hydrochemical evidence of transboundary interbasin ground-water flow, Chihuahua, Mexico and Trans-Pecos, Texas: Proceedings of the American Society of Civil Engineers, (Texas State Sec. Mtg), San Antonio, TX, p. 279 - 289.

Ashworth, J.B., Hibbs, B.J., and Peckham, D.S., 1995, Transboundary aquifers in the El Paso-Juarez-Las Cruces Region, the Texas Perspective: Proceedings of the American Society of Civil Engineers, (Texas State Sec. Mtg.), El Paso, TX, p. 332 - 336.

Hibbs, B.J., and Darling, B.K., 1995, Environmental isotopes and numerical models for understanding aquifer dynamics in southwestern basins: in Cleveland, T.G., ed., Advances in the Development and Use of Models in Water Resources, Herndon, VA, American Water Resources Association, p. 195 - 200.

Darling, B.K., Hibbs, B.J., Dutton, A.R., and Sharp, J.M., 1995, Isotope hydrology of the Eagle Mountains area, Hudspeth County, Texas - Implications for development of ground-water resources: in Hotchkiss, W.R., Downey, J.S., Gutentag, E.D., and Moore, J.E., eds., Water Resources at Risk, American Institute of Hydrology, Minneapolis, MN, p. SL12 - 24.

Hibbs, B.J., Darling, B.K., and Ashworth, J.B., 1995, Interbasin movement of ground water and vertical ground-water flow in Hudspeth County, Texas: Proceedings of Texas Water 95, a Component Conference of the First International Conference on Water Resources Engineering, American Society of Civil Engineers, San Antonio, TX, p. 267 - 277.

Hibbs, B.J., and Darling, B.K., 1995, Salinization of the Rio Grande alluvial aquifer in Hudspeth County, Texas: Proceedings of the 24th Water for Texas Conference, Research Leads the Way, Austin, TX, p. 157 - 161.

Ashworth, J.B., 1994, New emphasis on transboundary water resources: Proceedings of the American Water Resources Association, (Texas State Sec. mtg.), Factors affecting water resources, Austin, TX, p. 94 - 96.

Abstracts

Hibbs, B.J., 1997, Climate change and potential flow capacity in the southeastern Hueco aquifer - a numerical experiment: Geol. Soc. America Abs. with Programs (South Central/Rocky Mountain Sec.), v.29, p.14.

Hibbs, B.J., and Boghici, R., 1997, Temporal and spatial analysis of water levels and water quality in the Rio Grande and Rio Grande aquifer; El Paso/Ciudad Juarez to Ft. Quitman, Texas: Geol. Soc. America Abs. with Programs (South Central/Rocky Mountain Sec.), v.29, p.14.

Boghici, R., Hibbs, B.J., Ashworth, J.B., and Hayes, M.E., 1997, Impacts of ground-water development on the hydrogeology and hydrochemistry of the Hueco-Tularosa aquifer; Trans-Pecos, Texas and Chihuahua, Mexico: Geol. Soc. America Abs. with Programs (South Central/Rocky Mountain Sec.), v.29, p.4.

Darling, B.K., Hibbs, B.J., Dutton, A.R., and Sharp, J.M., 1997, Interbasin ground-water flow in Trans-Pecos, Texas: Geol. Soc. America Abs. with Programs (South Central/Rocky Mountain Sec.), v.29, p.7.

Hibbs, B.J., 1996, Cross-sectional modeling of ground-water flow on a transboundary flowline in Trans-Pecos, Texas and Chihuahua, Mexico: Geol. Soc. America Abs. with Programs (South Central Sec.), v.28, p.18.

Hibbs, B.J., 1996, Binational aquifer modeling along the El Paso/Juarez Corridor: Texas Civil Engineer, v.66, no.4, p.23.

Hibbs, B.J., and Darling, B.K., 1995, Sources of Salinity in the Rio Grande alluvial aquifer: New Waves, The Research Newsletter of the Texas Water Resources Institute, v.8, no.2, p.10.

Ashworth, J.B., Hibbs, B.J., and Peckham, D.S., 1995, Transboundary aquifers in the El Paso-Juarez-Las Cruces Region: Texas Civil Engineer, v.65, no.4, p.28.

Hibbs, B.J., Darling, B.K., and Peckham, D.S., 1994, Isotope hydrology and simulation of ground-water flow in the Red Light Draw bolson, a southwestern alluvial basin: Geol. Soc. America Abs. with Programs (Ann. Mtg.), v.26, p.A362.

New Mexico Team Participants

Public Presentations

Transboundary Aquifers in the El Paso-Juarez-Las Cruces Region, presented by Bobby Creel to Border 21 workshop, January 24, 1996, Las Cruces, New Mexico.

Transboundary aquifer study of El Paso, Juarez and Las Cruces area-Mesilla Valley groundwater sensitivity assessment, presented by Bobby Creel to meeting of Food and Agriculture Council, Water Quality Subgroup, March 6, 1996, Albuquerque, New Mexico.

Transboundary aquifer study of El Paso, Juarez and Las Cruces area-Mesilla Valley groundwater sensitivity assessment, presented by Bobby Creel to meeting of New Mexico Environment Department, Nonpoint

Source Task Force, April 4, 1996, Santa Fe, New Mexico.

Transboundary aquifer study of El Paso, Juarez and Las Cruces area, presented by Bobby Creel to meeting of New Mexico Geographic Information Council Spring Meeting, May 3, 1996, Albuquerque, New Mexico.

Transboundary aquifer study of El Paso, Juarez and Las Cruces, presented by Bobby Creel to meeting of TRIP Workshop, May 14, 1996, Ciudad Juarez, Mexico.

Transboundary aquifer study of El Paso, Juarez and Las Cruces area, presented by Bobby Creel to meeting of Governor's Cabinet Council-Subsurface data exchange workshop, July 12, 1995, Santa Fe, New Mexico.

Abstracts

Natural Sensitivity of the Mesilla Valley Basin of Southern New Mexico, poster/abstract by John F. Kennedy at 1995 Annual Meeting and Field Trip of the American Water Resources Association, New Mexico Section, October 12-13, 1995, Santa Fe, New Mexico.

Transboundary Aquifers in the El Paso-Juarez-Las Cruces Region, abs Creel, B., Samani, Z., Khandan, N., Hanson A., Stevens, K., Hann, P., Kennedy, J., and S. Hu; Texas Civil Engineer, 65:4, presented by J. Kennedy and P. Hann, ASCE Texas Section Fall Meeting, October 6, 1995, El Paso, Texas.

Transboundary aquifer study of El Paso, Juarez and Las Cruces area-Mesilla Valley groundwater vulnerability assessment, presentation by Bobby Creel and John Kennedy at the Southern New Mexico Regional GIS Symposium, September 14, 1995, Las Cruces, New Mexico.

APPENDIX C

GIS Coverages and Metadata Descriptions

GIS COVERAGES, METADATA DESCRIPTIONS, AND GROUND-WATER DATA SETS

One of the project goals was to compile available ground-water information into a geographically referenced format. The process of data compilation included identification of primary data sources, data acquisition, and format determination. Administration of this joint effort required that common standards be developed to facilitate the transfer of working information between cooperators. Facilitation of data compilation by uniquely different entities such as NMWRRI and TWDB into a single useable document required use of a common GIS application software, development of a base illustration, and a common coordinate system. ARC/INFO 7.0.3 on the UNIX platform was chosen as the underlying software basis for the project.

The base illustration consists of transportation, political boundaries, and the study area boundary. The transportation and political boundaries are from the TIGER 1990 data files, some corrections to arc referencing information was made in the development of the transportation coverage. The study area boundaries correspond to the political boundaries in the United States. The boundary in Mexico was generated with political and logical boundaries based on extension of US boundary limits. The common coordinate system adopted for the project is described in the projection files associated with each coverage and is:

Projection:	Lambert
Units:	Meters
Spheroid:	GRS1980
Parameters:	
1st Standard Parallel	32 30 0.000
2nd Standard Parallel	31 30 0.000
Central Meridian	-106 0 0.000
Latitude of Projection's Origin	32 0 0.000
False Easting (meters)	1000000.00000
False Northing(meters)	1000000.00000

The primary data sets (wells, aquifers, and geology) were compiled and visually checked. Summary illustrations from these coverages have been developed along with a one page description. The metadata format has been developed to meet or exceed minimum FDGC requirements and are associated with the appropriate coverage file. The secondary data sets have a metadata file developed by the originator which is included with the data file and the study reference only lists origin.

Coverages

The following is a listing of the regional illustrations, primary data coverages, and file names for data retrieval from the accompanying CD.

Regional Illustrations

Location of Study Area
Aquifers
Economically Distressed Areas
Well Locations
Geology
Land Surface Relief With Drainage
Landuse
Hazardous Waste Sites and Landfills

Arc/Info Coverages Developed by the TWDB

Category	File	Description
Aquifers	trans_tula.e00	Tularosa aquifer
	trans_hueco.e00	Hueco aquifer
	se_hueco.e00	Southeastern Hueco aquifer
	trans_mesi.e00	Mesilla aquifer
	trans_grande.e00	Rio Grande aquifer
	jornada.e00	Jornada aquifer
	cretace_3.e00	Diablo Plateau aquifer
Study Area Boundary	transelpaso.e00	Study area
Economically Distressed Areas (EDAs)	elpaso_col.e00	El Paso Co. colonias
	huds_colon.e00	Hudspeth Co. colonias
	nm_colonias.e00	New Mexico colonias
Well Locations	ephud_wells.e00	El Paso & Hudspeth Co. Wells
	otwells_p.e00	Otero Co. Wells
	dac_wells.e00	Dona Ana Co. Wells
	mex_wells.e00	Mexican wells
	juarez_wells.e00	Juarez wells
	irrga_wells.e00	Mexican irrigation wells

Water Level Contours	rg_wl73.e00	Rio Grande aquifer water levels (1973-74)
	rg_wl94.e00	Rio Grande aquifer water levels (1994-95)
	huetul_wl.e00	Hueco-Tularosa aquifer water levels
	sehu_wl.e00	Southeastern Hueco aquifer water levels
	diablo_wl.e00	Diablo Plateau aquifer water levels
Rock Outcrops	rock_out.e00	Rock outcrops on report maps

Arc/Info Coverages Obtained From Outside Sources

Data	File	Source
Relief	Image only	USGS DEM data
Landuse		USGS Landuse data
		(1:250,000 scale)
Hazardous Waste & Landfill Sites	lanf_elp.e00	USEPA
	haz_elp.e00	
	trans_fill.e00	
Geology		Corps of Engineers GRASS data
Texas	marf_geo.e00	BEG mapsheets
	elp_geo.e00	(1:250,000 scale)
Mexico	mexgeo.e00	NMSU map sheets
		(1:1,000,000 scale)
New Mexico	nm_geo_clip.e00	NMSU map sheets
		(1:500,000 scale)
Cities, Roads, Railroads, Drainage, Landmarks		
Texas & New Mexico	trans_city.e00	TIGER 1990 census data
	elpaso_rds.e00	
	hudspethrds_p.e00	
	trans_rails.e00	
	otero_p.e00	
	dona_ana.e00	
Mexico	mex_cult1.e00	INEGI 1:250,000 topo sheets
	mex_city1.e00	
	mex_trans.e00	

GIS Metadata Descriptions

The GIS metadata descriptions for the above Arc/Info coverages are included on the CD as text files in the directory "METADATA".

Ground-Water Data Sets

The ground-water databases included on the attached CD have been provided by the participating agencies: Texas Water Development Board and New Mexico State University Water Resources Research Institute for the U.S. side, and Comision National del Agua , Junta Municipal de Agua Y Saneamiento, Ciudad Juarez, and Servicios Nacionales de Estatistica, Geografia e Informatica (INEGI) for the Mexican side.

The general types of data provided with the report 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. 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. Each workbook consists of spreadsheets named for the type of data they contain, as shown below:

Workbook name: SUMPUMP
Sheet name: Contains total annual pumping volumes (in m3) for El Paso and Hudspeth Counties between the years 1980 and 1992.

Workbook name: TEXAS.XLS
Sheet name: INDPUMP
Contains annual and monthly industrial pumping volumes (in m3) for El Paso and Hudspeth Counties between 1955 and 1994.

Workbook name: TEXAS.XLS
Sheet name: MUNPUMP
Description: Contains annual and monthly municipal pumping volumes (in m3) for El Paso and Hudspeth Counties between 1955 and 1994.

Workbook name: TEXAS.XLS{1}
Sheet name: WELL DATA
Description: Contains general information about water wells in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: WATER QUALITY
Description: Contains results of water quality analyses (major ions) for ground water in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: INFREQUENTS
Description: Contains results of water quality analyses (trace metals, halides,stable and radioactive isotopes, organic compounds, etc.) for ground water in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: WATER LEVELS
Description: Contains water level measurements in wells in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: AQUIFER LIST
Description: Contains a listing of all known aquifers in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: CASINGS
Description: Contains casing data for wells in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: STORETS
Description: Contains descriptions for all measured physical and chemical parameters for ground water in El Paso and Hudspeth Counties.

Workbook name: TEXAS.XLS
Sheet name: REMARKS
Description: Contains additional general comments regarding water wells in El Paso and Hudspeth Counties.

Workbook name: NEW MEXICO.XLS{2}
Sheet name: WELL DATA
Description: Contains general information about water wells in Otero and Dona Ana Counties.

Workbook name: NEW MEXICO.XLS
Sheet name: WATER LEVELS
Description: Contains water level measurements in wells in Otero and Dona Ana Counties.

Workbook name: NEW MEXICO.XLS
Sheet name: WATER QUALITY
Description: Contains results of water quality analyses (major ions) for ground water in Otero and Dona Ana Counties.

Workbook name: NEW MEXICO.XLS
Sheet name: INFREQUENTS
Description: Contains results of water quality analyses (trace metals, halides, stable and radioactive isotopes, organic compounds, etc.) for ground water in Otero and Dona Ana Counties.

Workbook name: MEXICO.XLS
Sheet name: WATER LEVELS (JMAS)
Description: Contains water level measurements in Ciudad Juarez and surrounding area. Data supplied by Junta Municipal de Agua Y Saneamiento (JMAS).

Workbook name: MEXICO.XLS
Sheet name: WATER LEVELS (CNA)
Description: Contains water level measurements in Juarez Valley. Data supplied by Comision Nacional del Agua (CNA).

Workbook name: MEXICO.XLS
Sheet name: WATER QUALITY (JMAS)
Description: Contains results of water quality analyses (major ions) for ground water in Ciudad Juarez and surrounding area. Data supplied by Junta Municipal de Agua Y Saneamiento (JMAS).

Workbook name: MEXICO.XLS
Sheet name: WATER QUALITY (CNA)
Description: Contains results of water quality analyses (major ions) for ground water in Juarez Valley. Data supplied by Comision National del Agua (CNA).

Workbook name: MEXICO.XLS
Sheet name: CORE DESCRIPTIONS (CNA)
Description: Contains lithological descriptions of cores from wells in Juarez Valley. Data supplied by Comision National del Agua (CNA).

Workbook name: MEXICO.XLS

Sheet name: CORE DESCRIPTIONS (JMAS)

Description: Contains lithological descriptions of cores from wells in Ciudad Juarez. Data supplied by Junta Municipal de Agua Y Saneamiento (JMAS).

Workbook name: MEXICO.XLS

Sheet name: LAND USE

Description: Shows the cultivated crops and corresponding number of hectares for Juarez Valley.

Workbook name: MEXICO.XLS

Sheet name: PUMPAGE (CNA)

Description: Contains annual and monthly pumping volumes (in thousands of m3) for wells in Juarez Valley between the years 1989 and 1995.

Workbook name: MEXICO.XLS

Sheet name: PUMPAGE (JMAS)

Description: Contains annual and monthly pumping volumes (in m3) for wells in Ciudad Juarez between the years 1990 and 1994.
Data supplied by Junta Municipal de Agua Y Saneamiento (JMAS).

Workbook name: MEXICO.XLS

Sheet name: WATER QUALITY (INEGI)

Description: Contains results of water quality analyses (major ions) for ground water in Juarez Valley. Data entered from the INEGI map sheets.

Workbook name: MEXICO.XLS

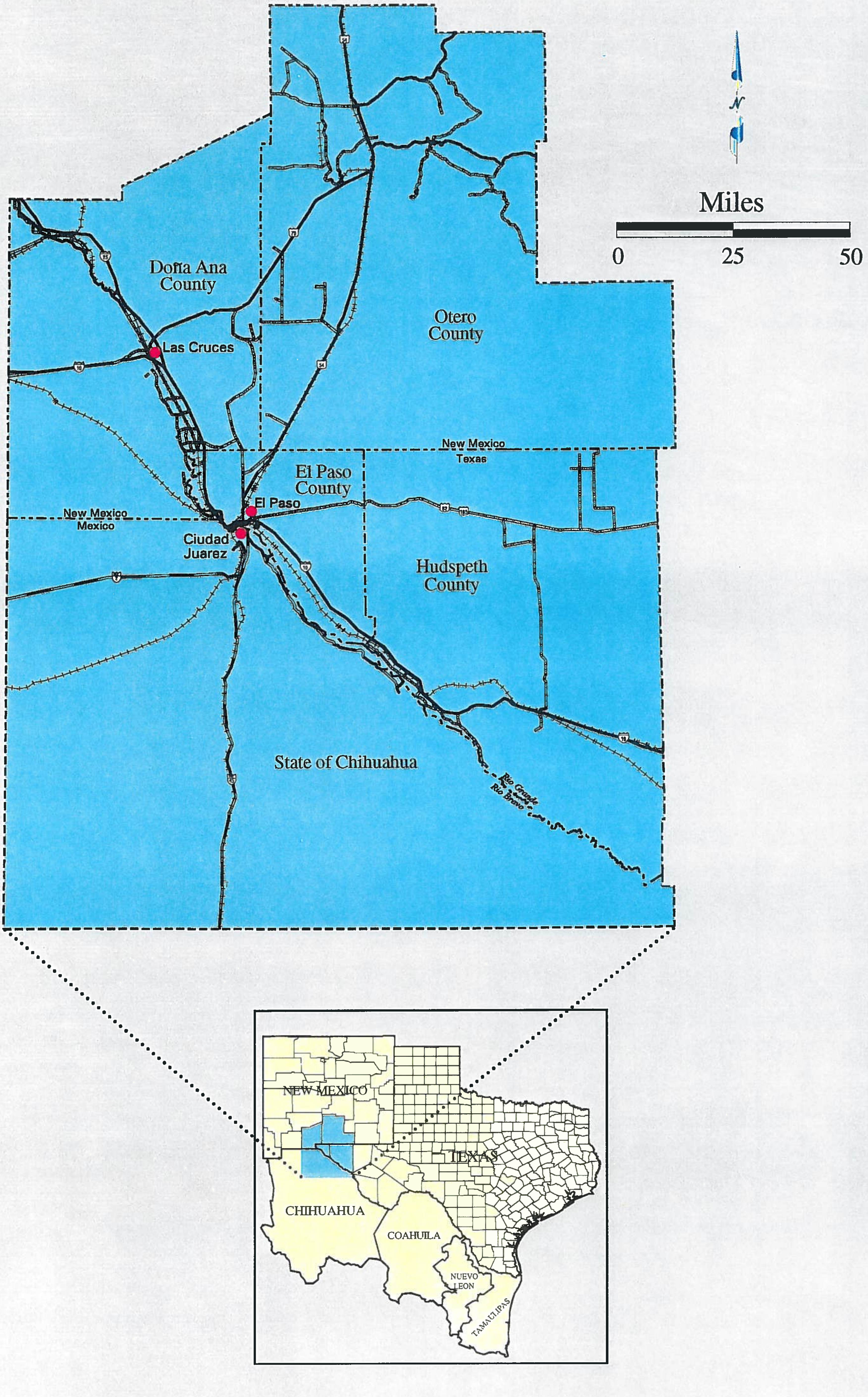
Sheet name: LATLONG

Description: Contains geographical coordinates for wells in Ciudad Juarez. Data derived from maps supplied by Comision Nacional del Agua.

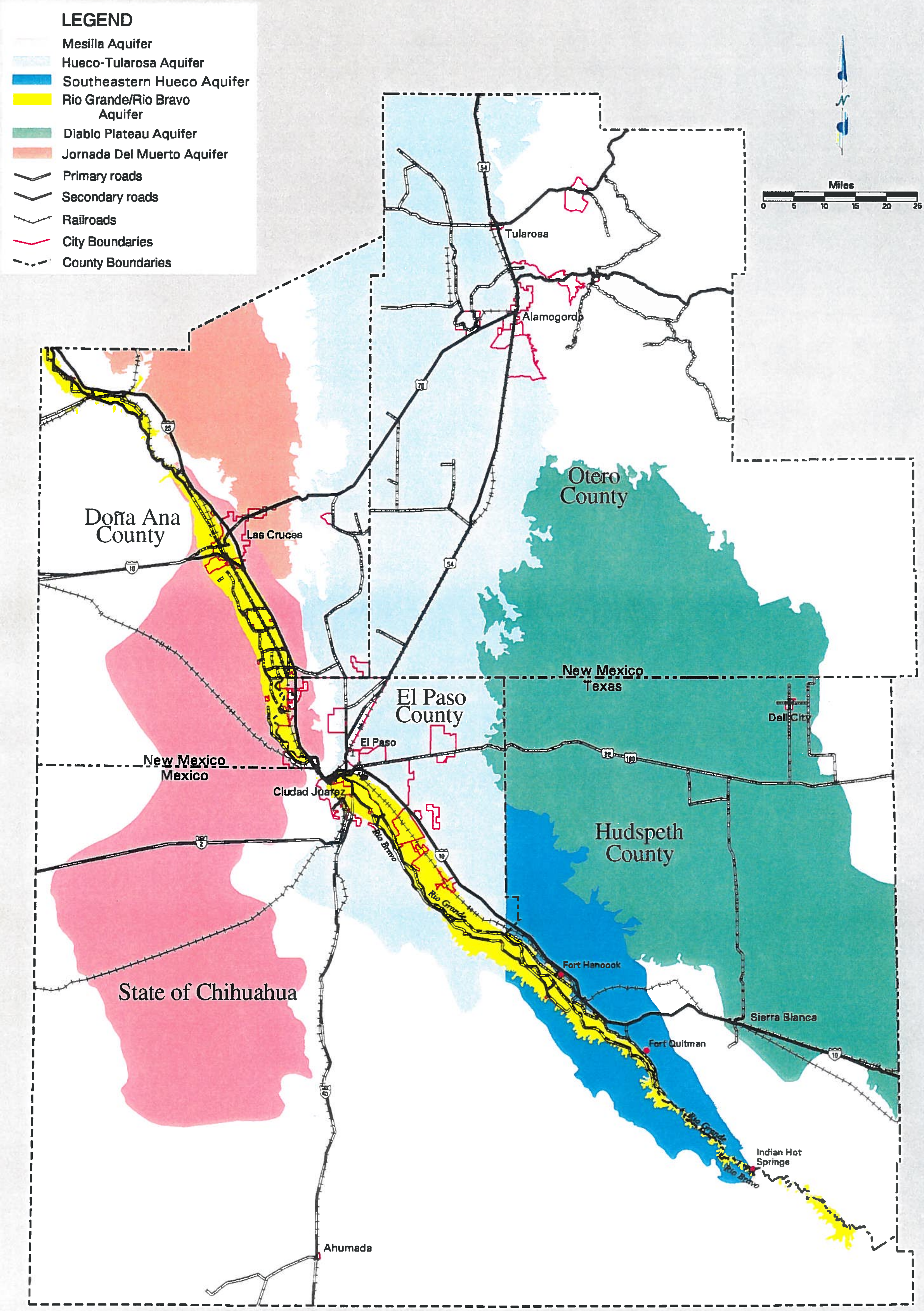
FOOTNOTES********************************

{1} Please refer to document REFGUIDE.DOC for explanation of codes used in the TEXAS.XLS database

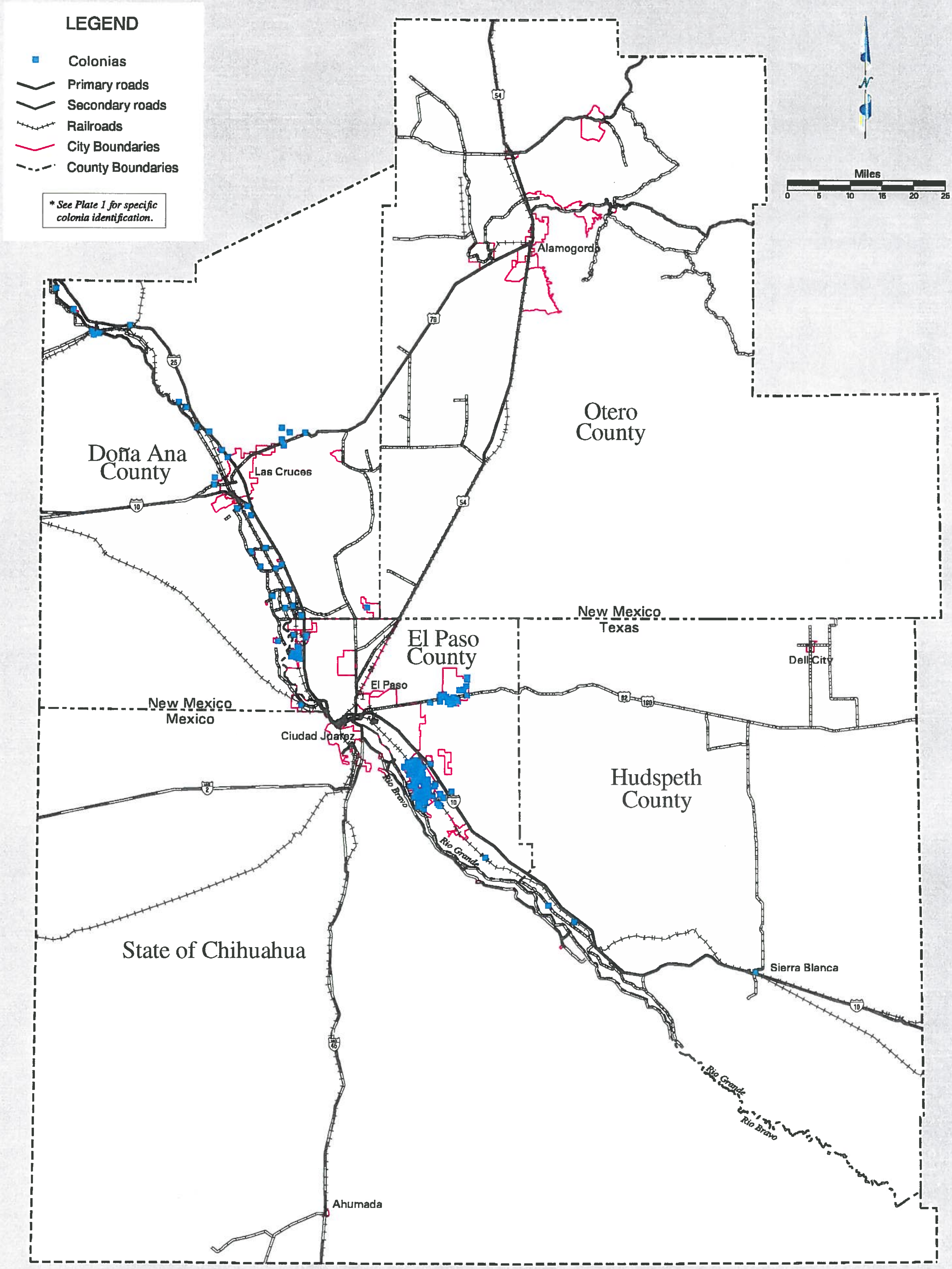
{2} Please refer to document TULACODE.DOC for explanation of codes used in the NEW MEXICO.XLS database



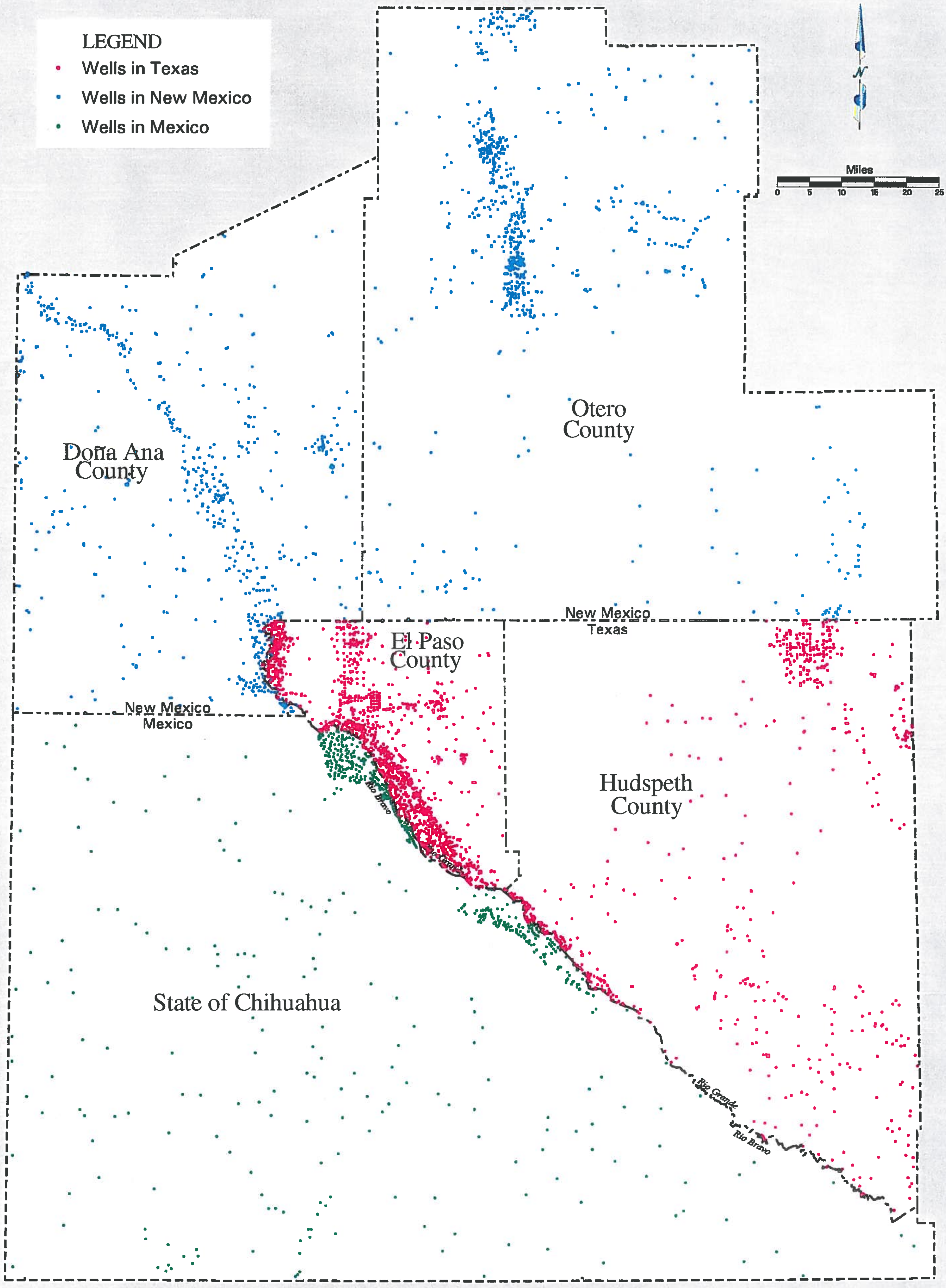
LOCATION OF STUDY AREA



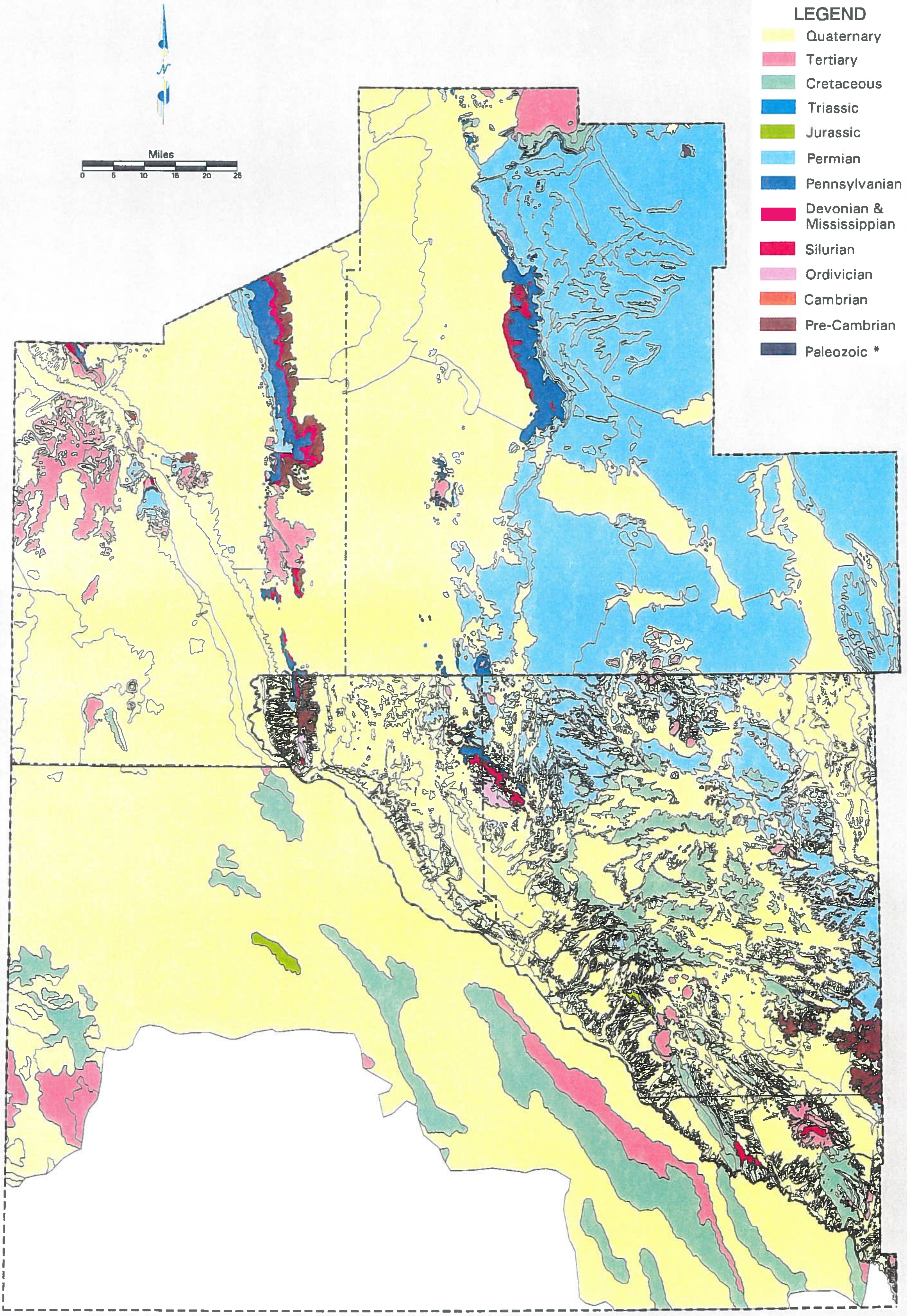
REGIONAL AQUIFERS



ECONOMICALLY DISTRESSED AREAS
(In the United States)



WELL LOCATIONS


LEGEND
Quaternary
Tertiary
Cretaceous
Triassic
Jurassic
Permian
Pennsylvanian
Devonian & Mississippian
Silurian
Ordivician
Cambrian
Pre-Cambrian
Paleozoic *
Miles
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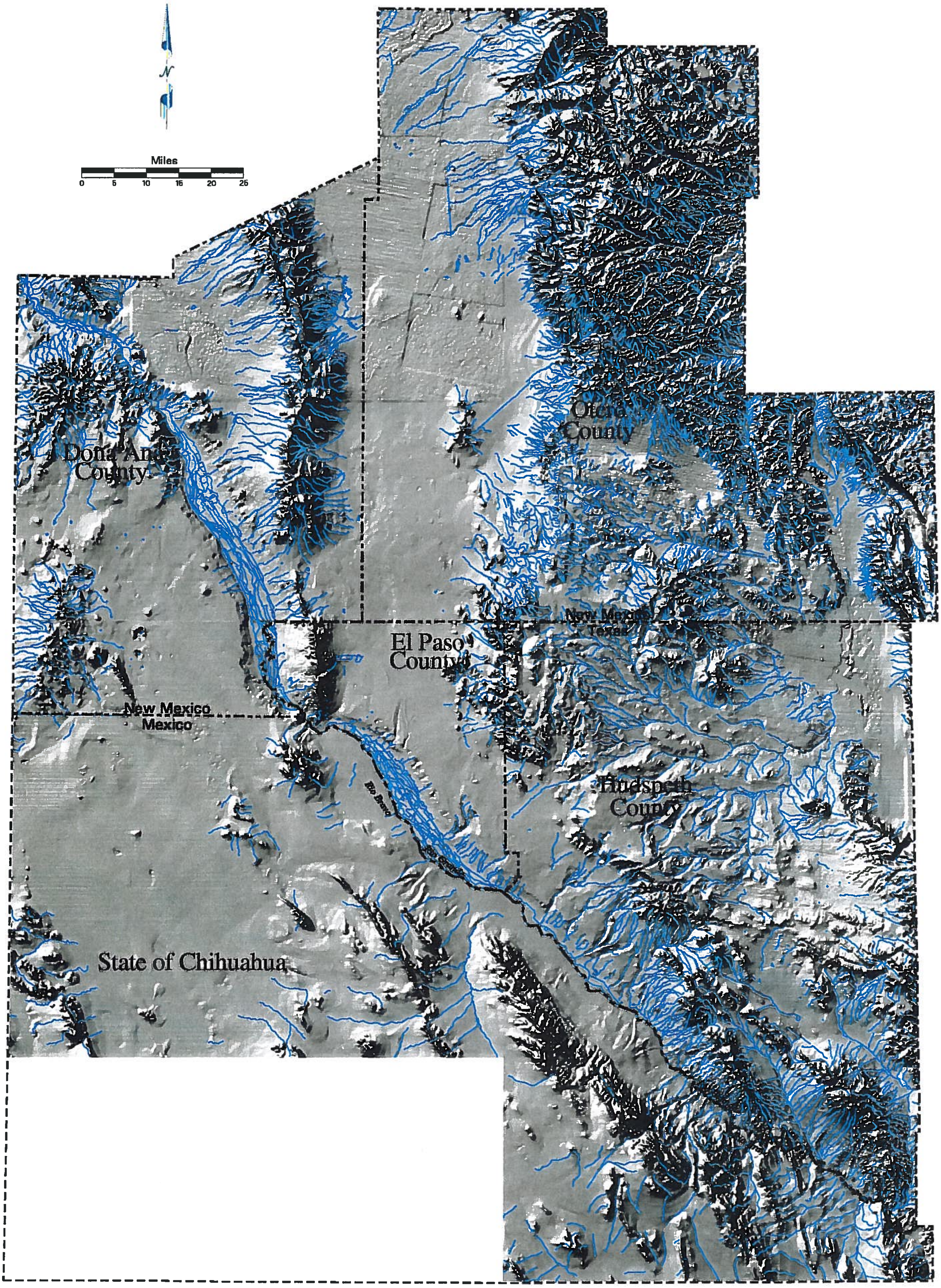
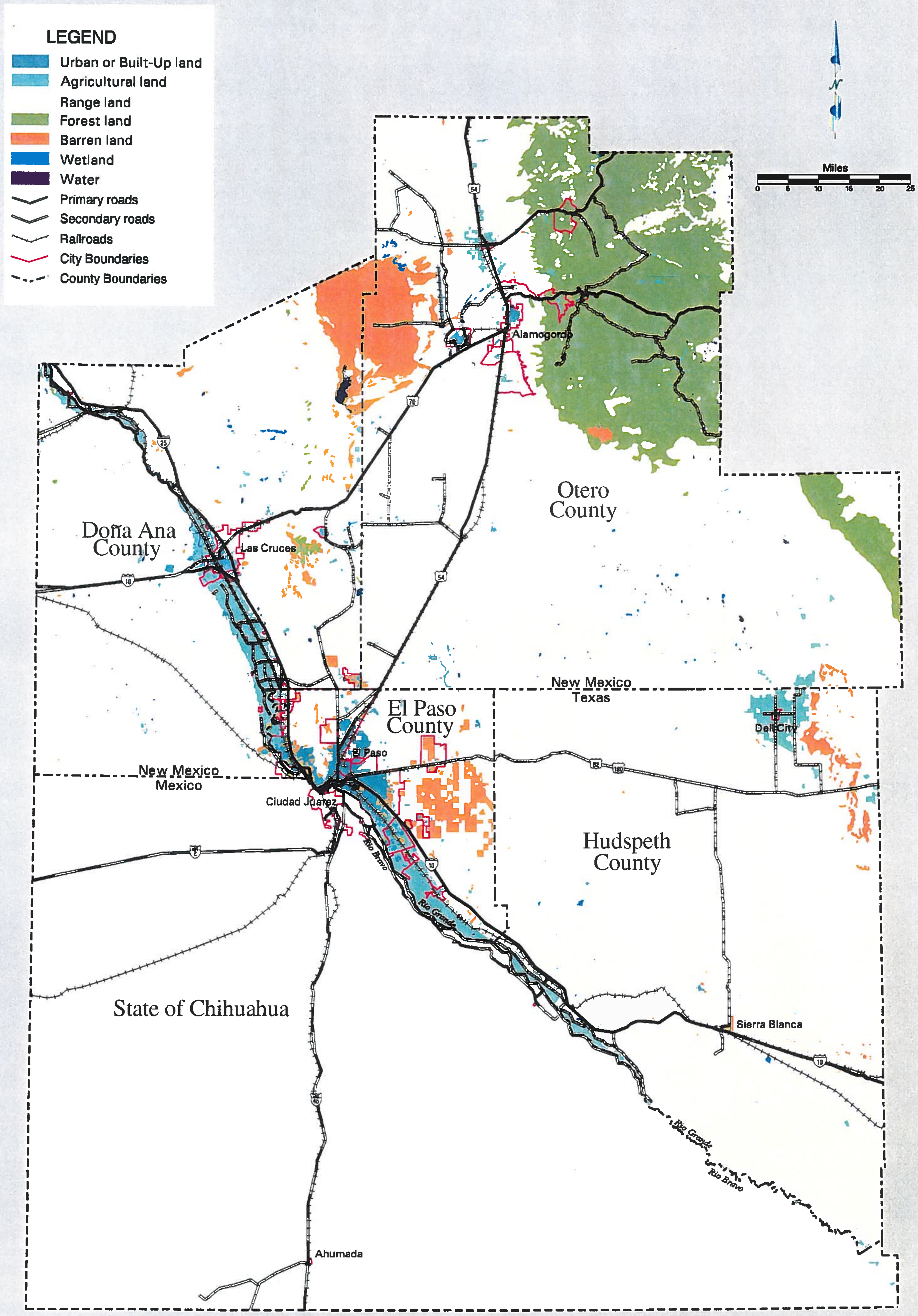
25
N

GEOLOGY

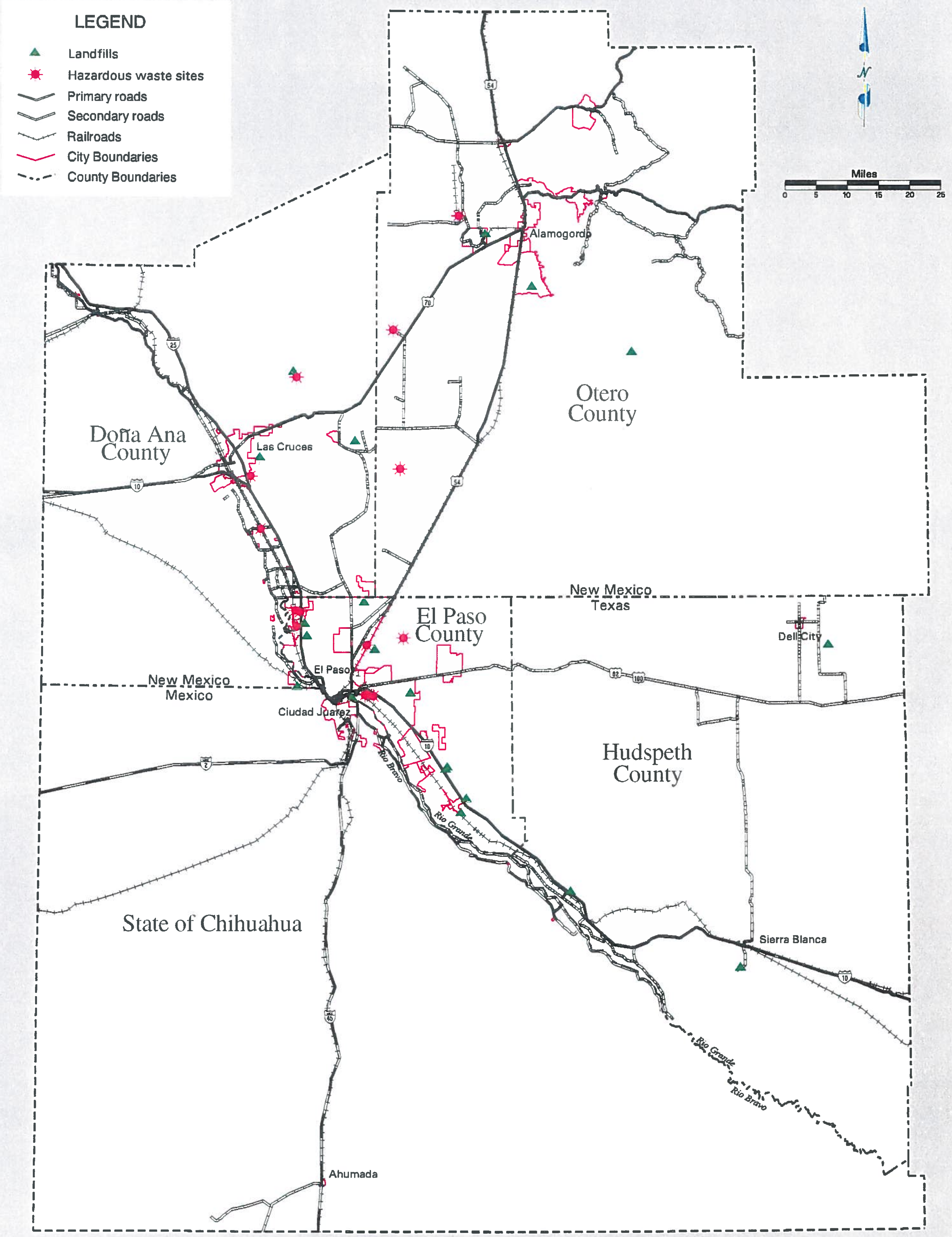


LAND SURFACE RELIEF WITH DRAINAGE



LANDUSE

(In the United States)



LANDFILLS AND HAZARDOUS WASTE SITES

(In the United States)