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.

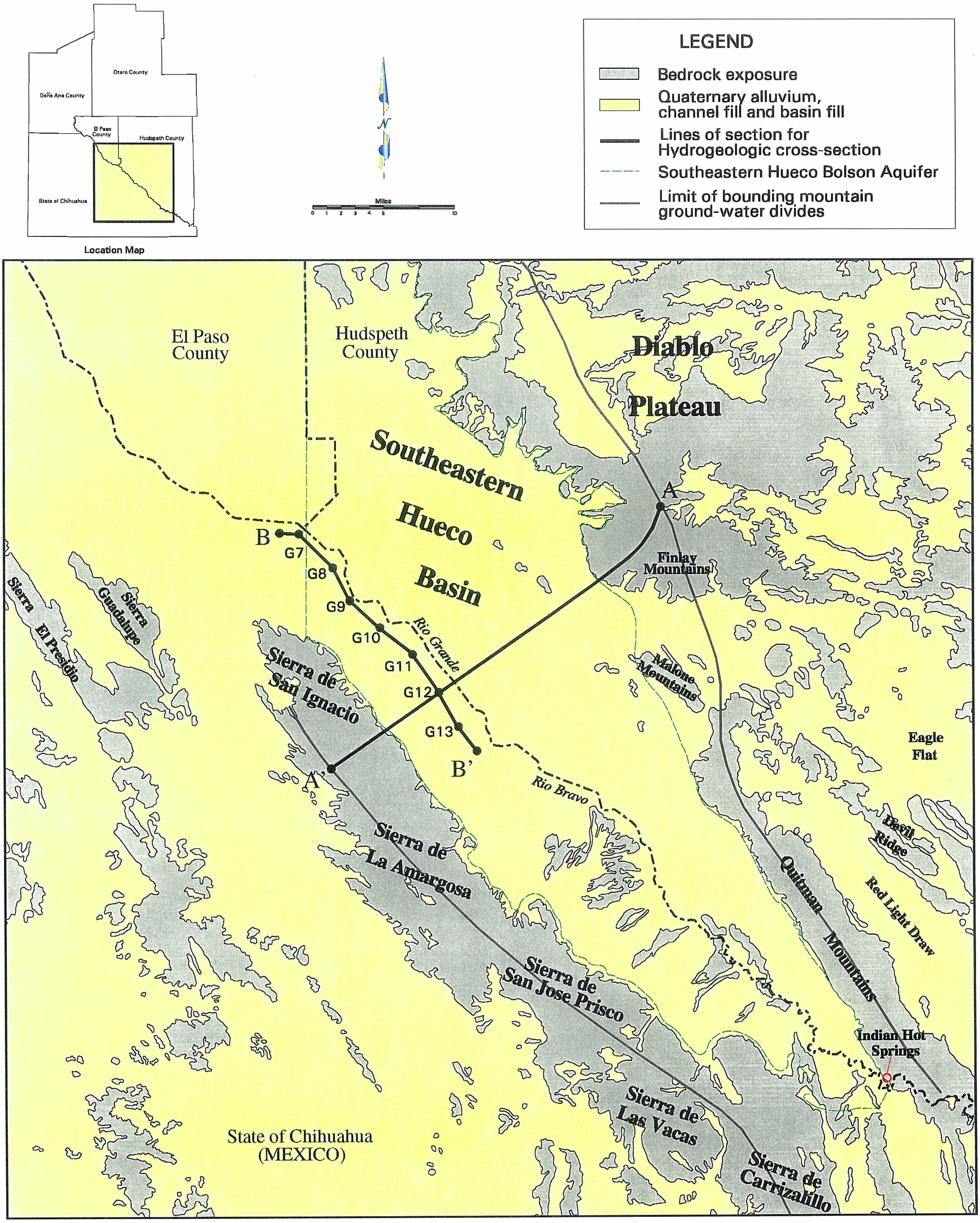

Figure 4.1. Location and extent of the southeastern Hueco aquifer. Map shows the limits of the southeastern Hueco Bolson aquifer as well as the limits of the bounding mountain ground-water divides that define the full extent of the aquifer (bolson fill and flanking highlands).

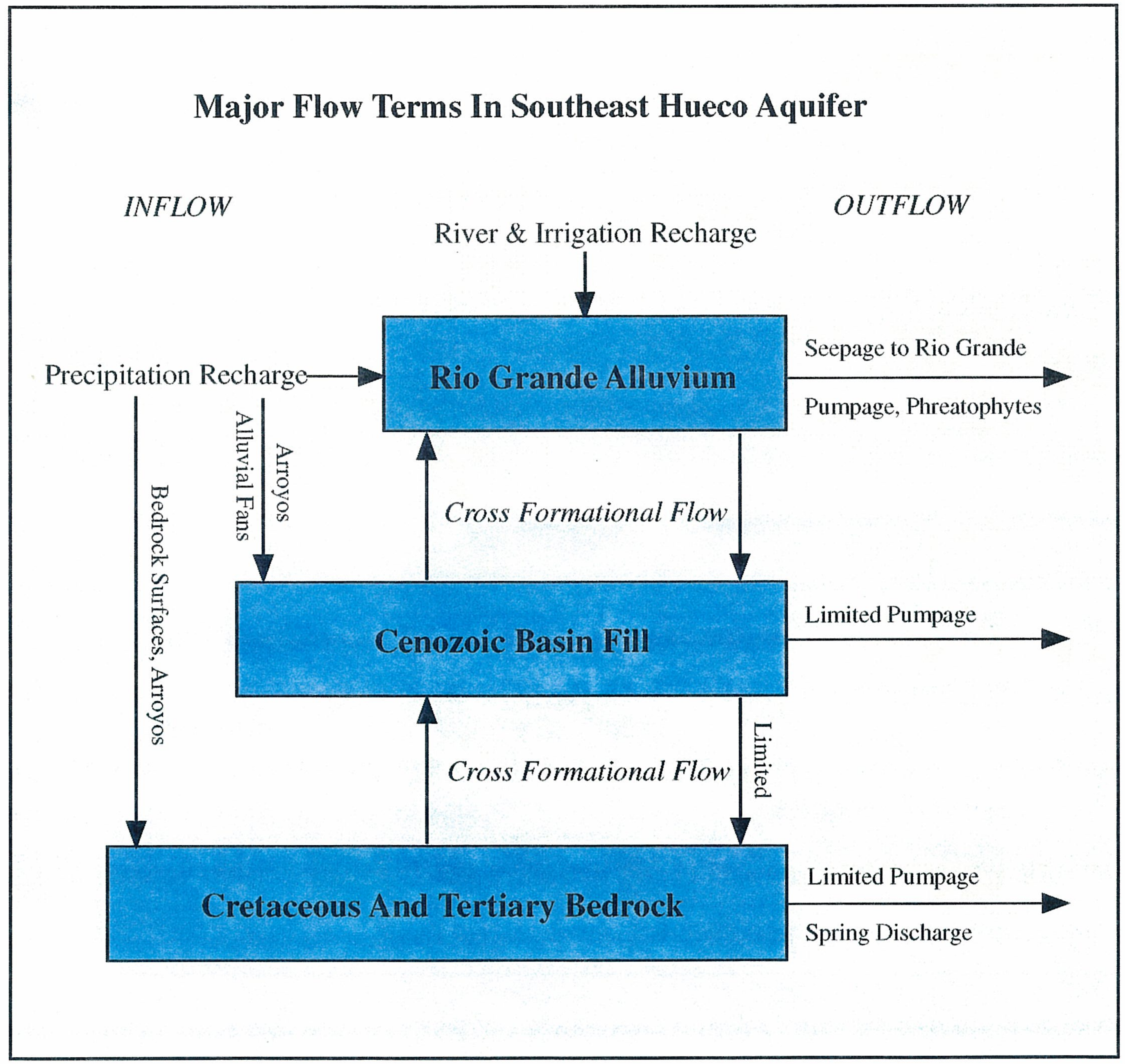

Figure 4.2. Major flow components in the southeastern Hueco aquifer.

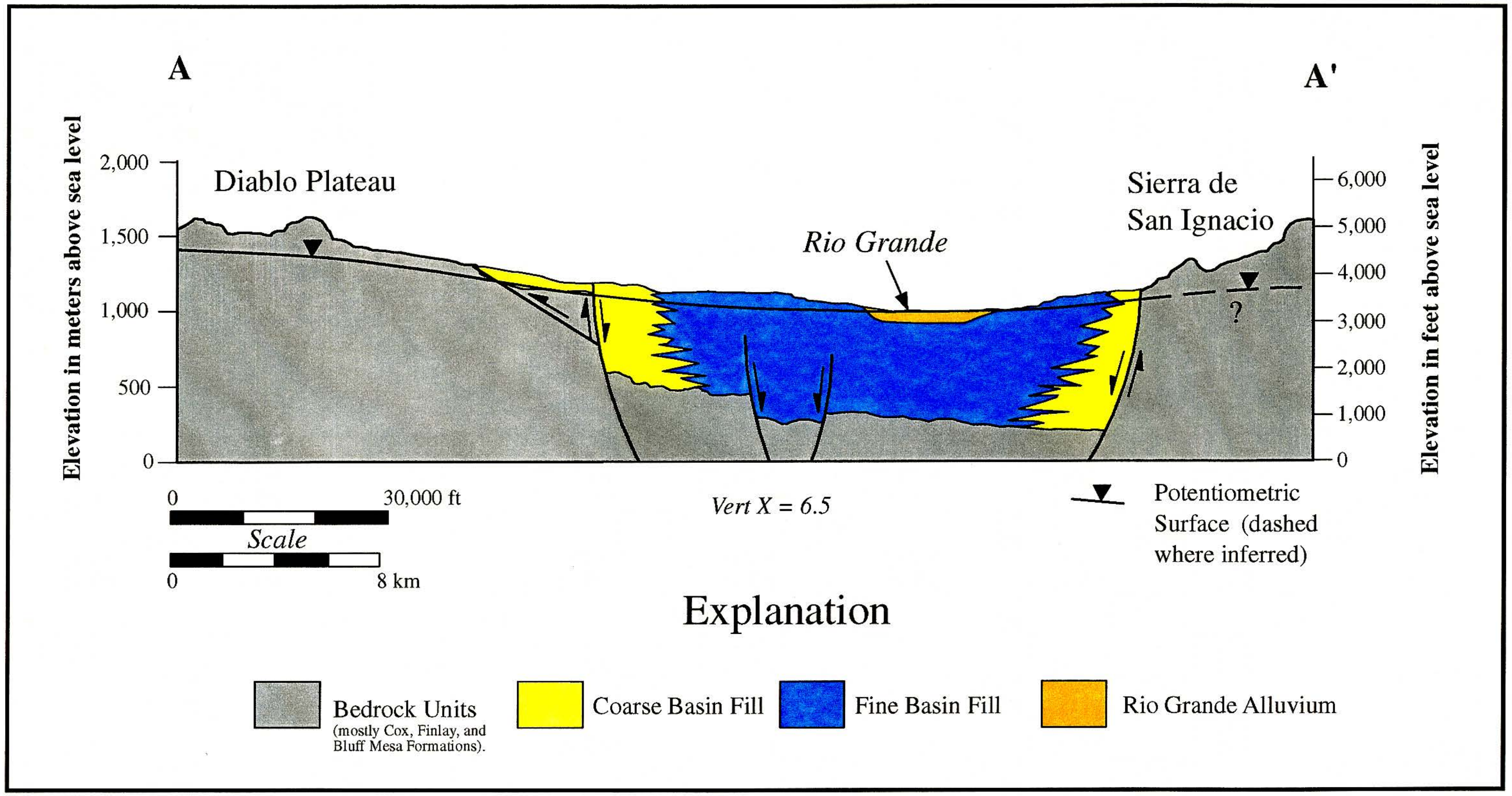

Figure 4.3. Generalized hydrogeologic cross section A - A' (line of section shown in Figure 4.1. Basin fill/bedrock contact selected from maps prepared by Collins and Raney, 1991, and from test-hole logs and geophysical logs in the Texas Water Development Board files).

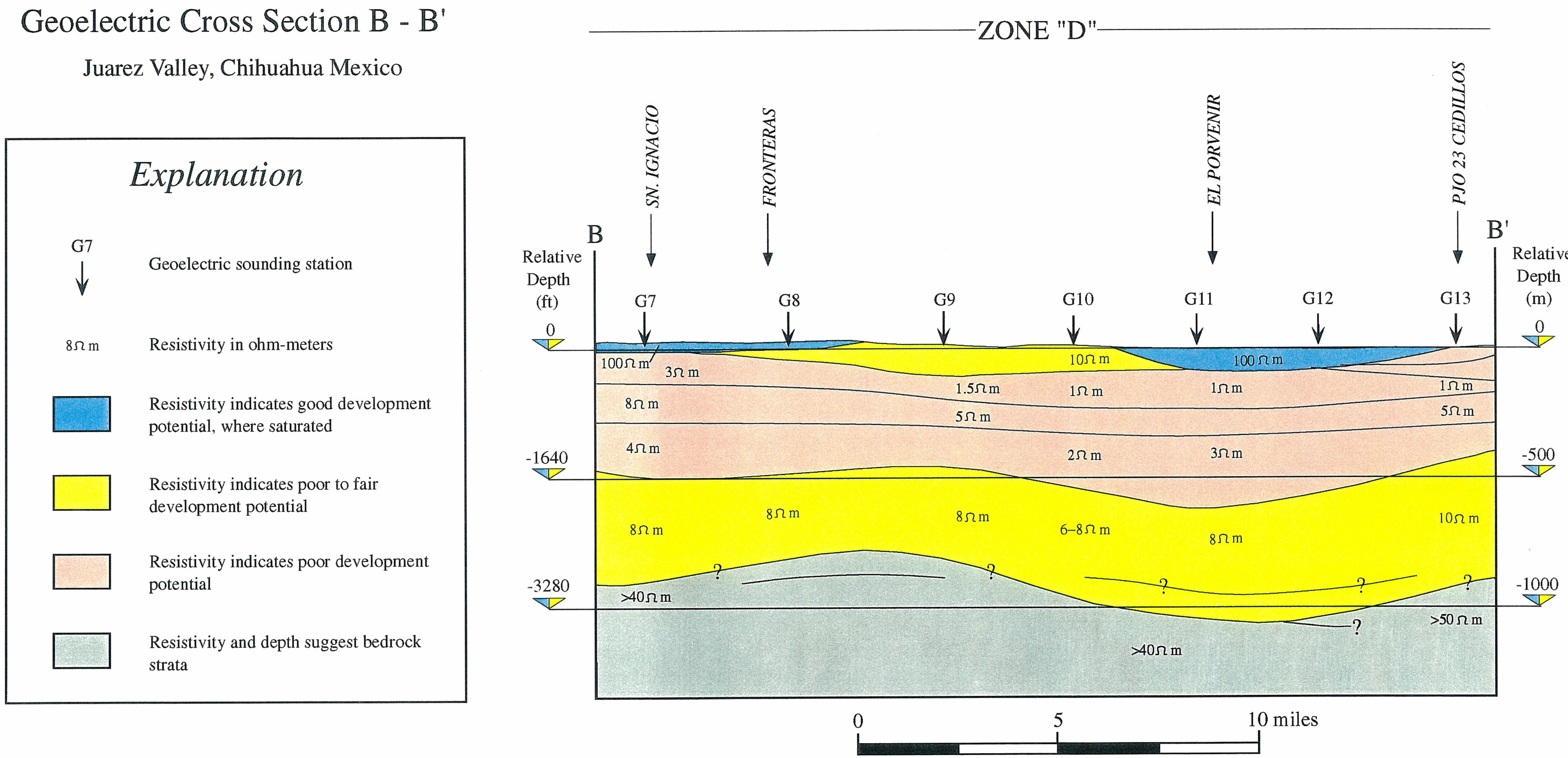

Figure 4.4. Geoelectric cross section B - B' across the southeastern Hueco aquifer, northern Chihuahua, Mexico. The map shows interpreted average real resistivities (modified from Geo Fimex, 1970; line of section shown on Figure 4.1).

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 $\pm$ 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

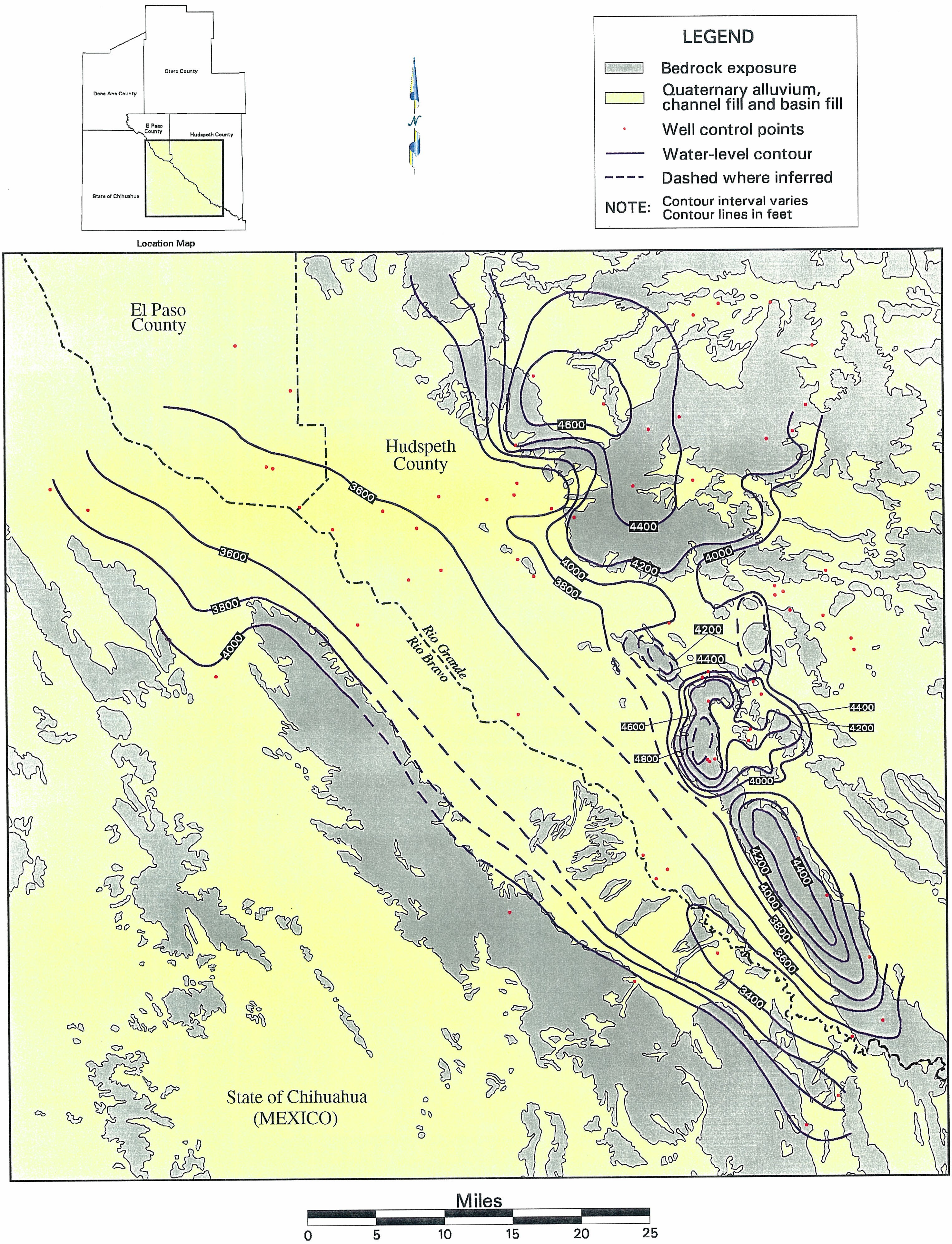

Figure 4.5. Regional potentiometric surface map for the southeastern Hueco aquifer and surrounding mountains and plateaus.(source of data, Fisher and Mullican, 1990; Texas Water Development Board; Comision Nacional del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

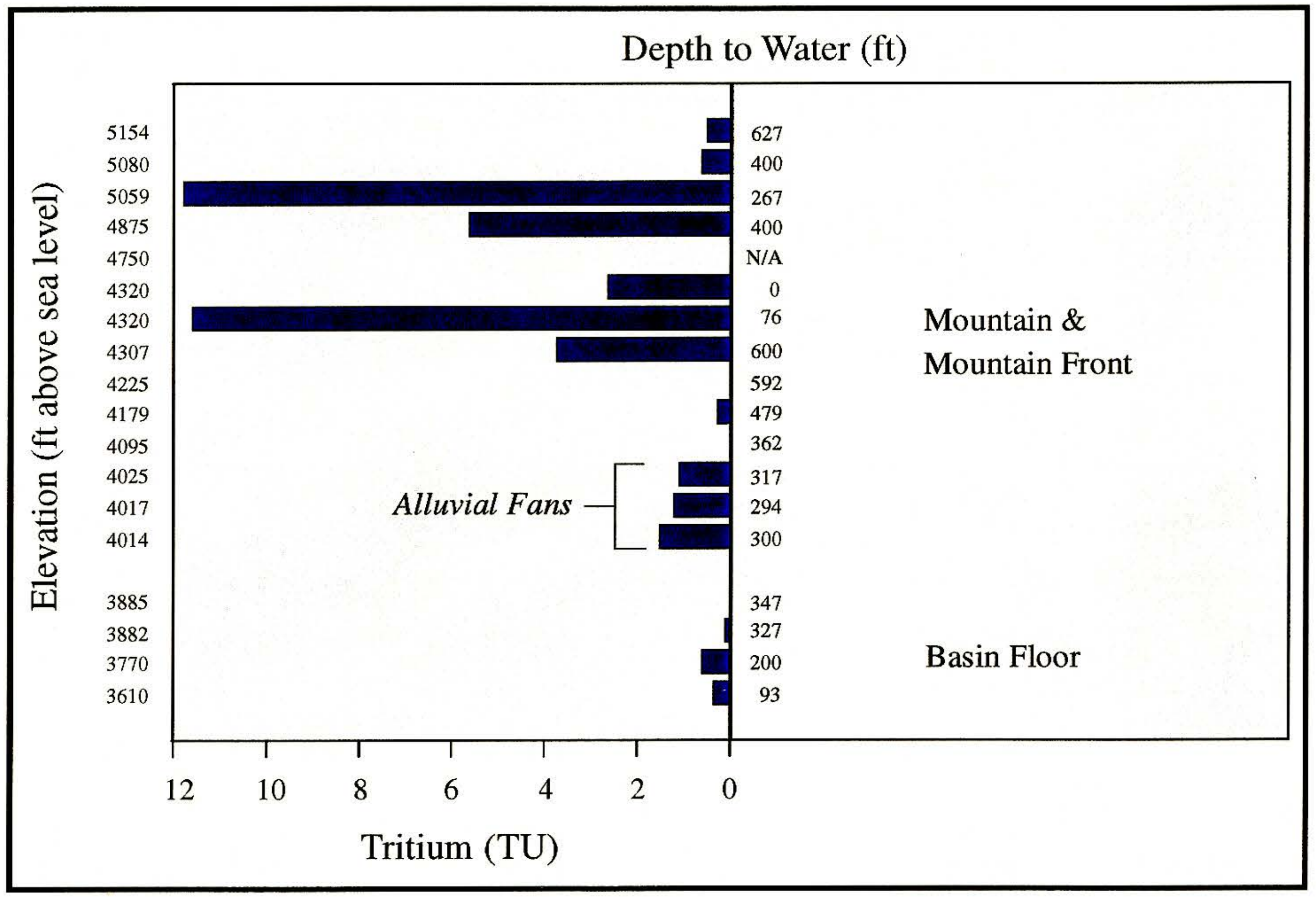

Figure 4.6a. Tritium activities (TU) in highland (mountain and mountain front) and lowland (basin floor) areas of the southeastern Hueco aquifer indicate that precipitation recharge occurs primarily within the upper mountains and plateaus (source of data, Fisher and Mullican, 1990).

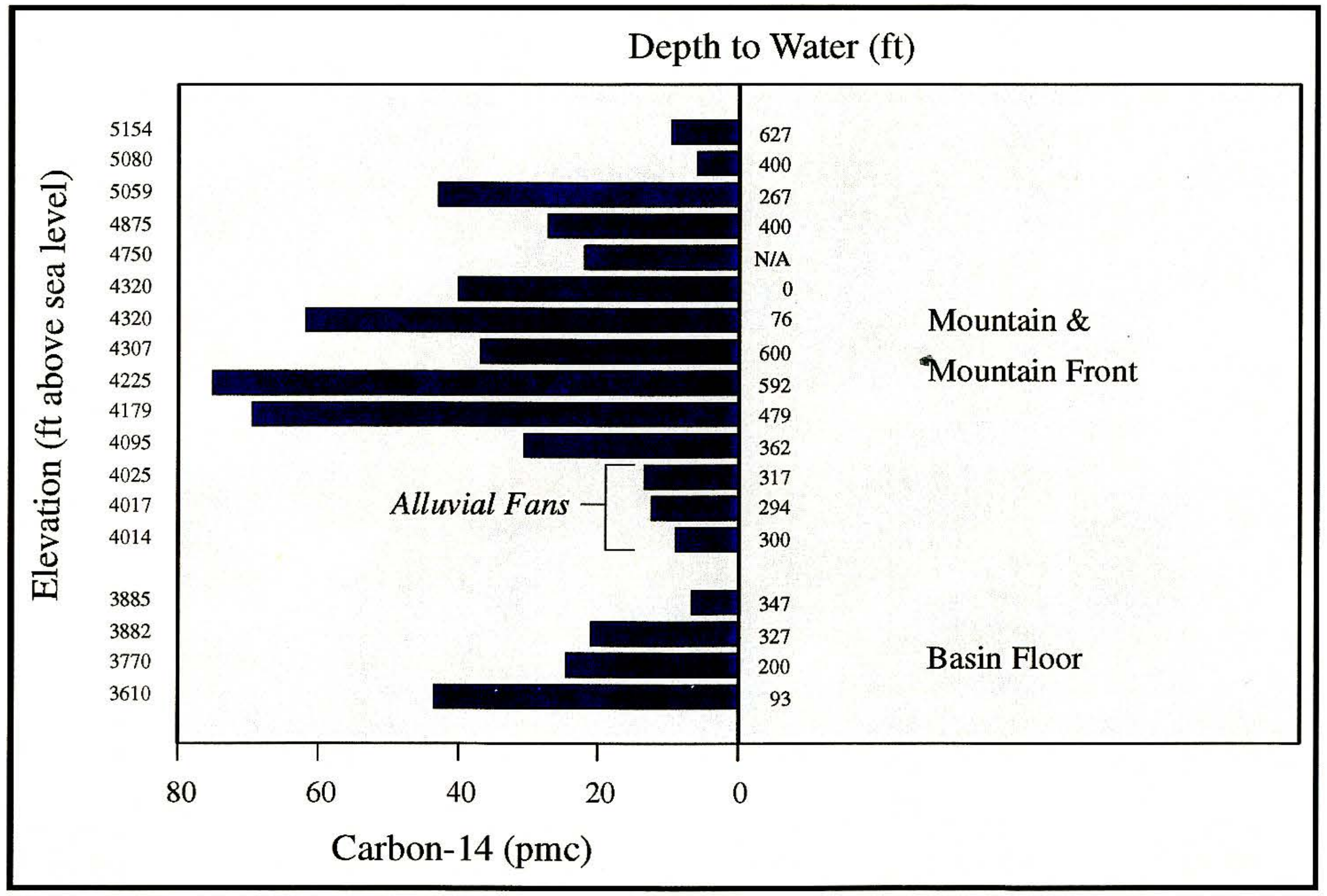

Figure 4.6b. Percentages of carbon-14 in highland (mountain and mountain front) and lowland (basin floor) areas of the southeastern Hueco aquifer indicate that precipitation recharge occurs primarily within the upper mountains and plateaus (source of data, Fisher and Mullican, 1990).

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.

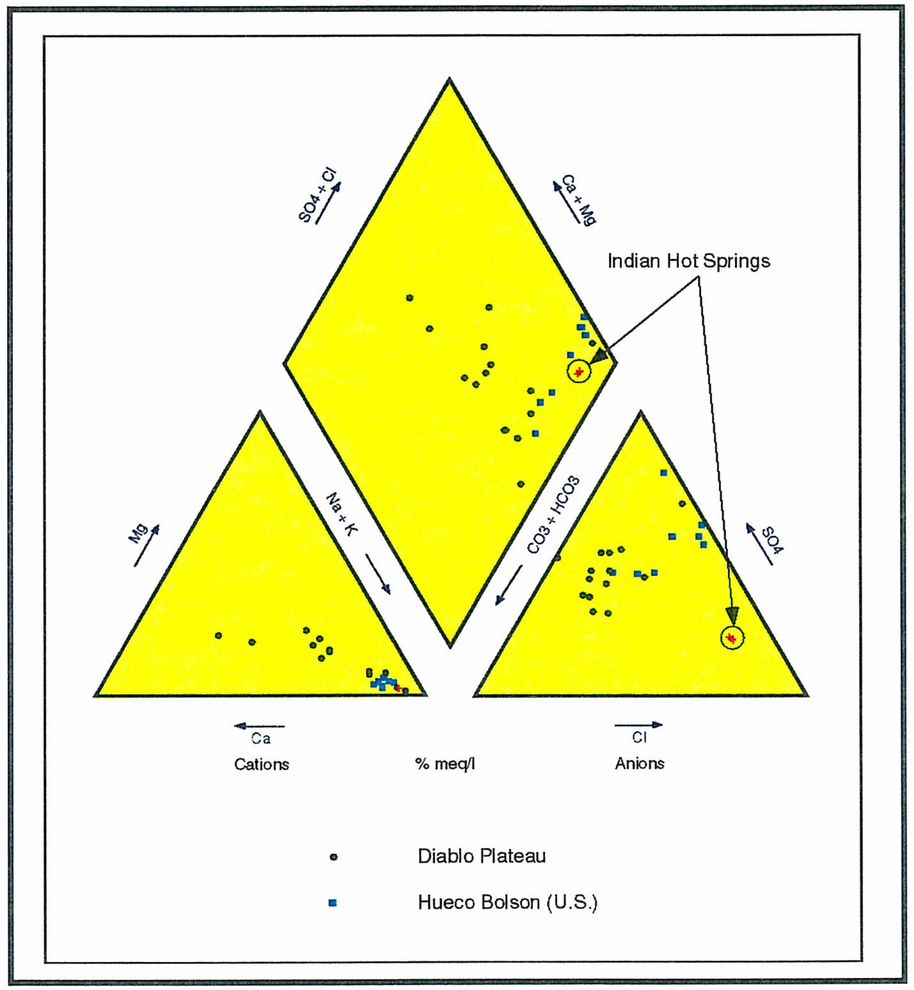

Figure 4.7a. Hydrochemical Piper plot for the bedrock (mountain and plateau) strata, bolson strata, and Indian Hot Springs in the U.S. part of the southeastern Hueco aquifer. Piper plot indicates distinct hydrochemical types for these water bearing strata in the southeastern Hueco aquifer (source of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

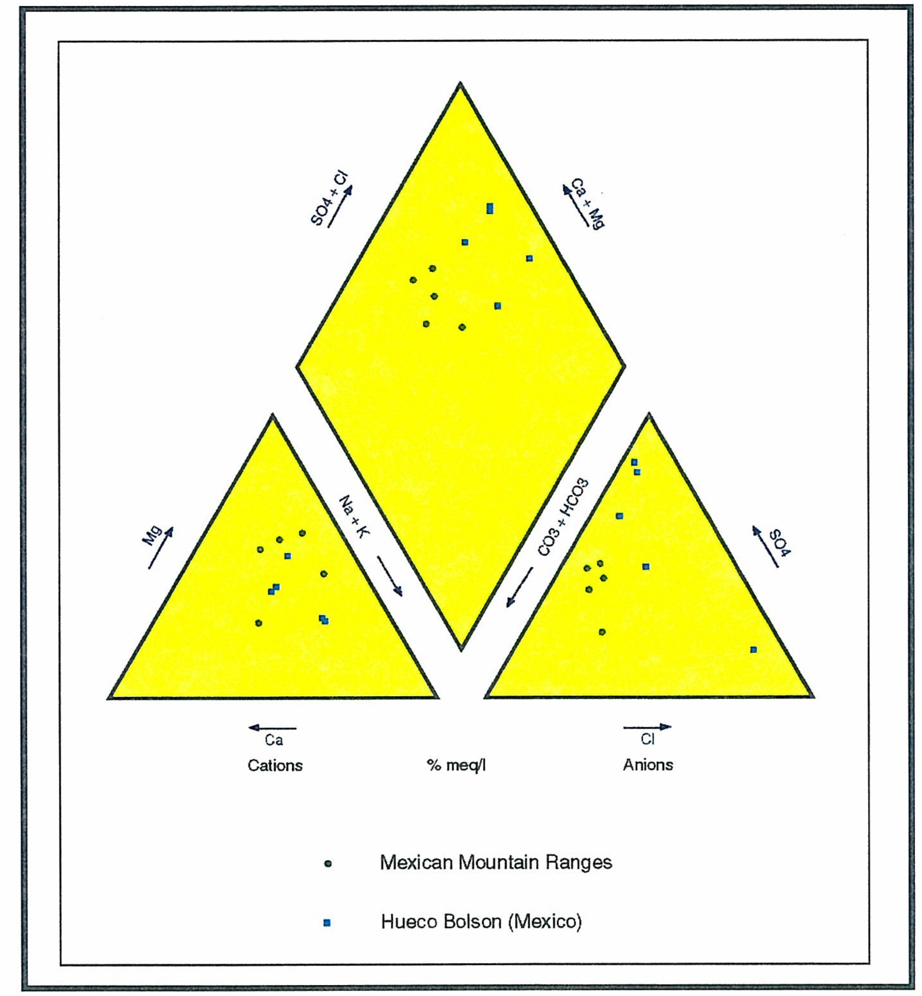

Figure 4.7b. Hydrochemical Piper plot for the bedrock (mountain) strata and bolson strata in the Mexican part of the southeastern Hueco aquifer. Piper plot indicates distinct hydrochemical types for these water bearing strata in the southeastern Hueco aquifer (source of data, Comision Nacional Del Agua;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

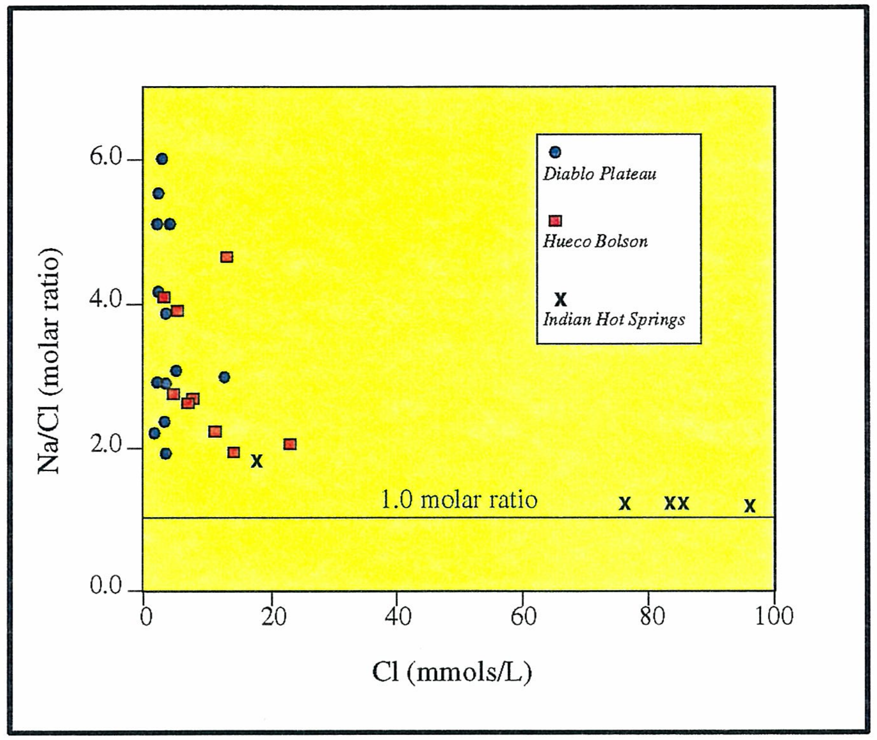

Figure 4.8a. Scatter plot showing (Na/Cl) molar ratios vs molar Cl for samples collected from bedrock strata, bolson strata, and Indian Hot Springs, U.S. (source of data, Fisher and Mullican, 1990; Darling and others, 1994; Texas Water Development Board).

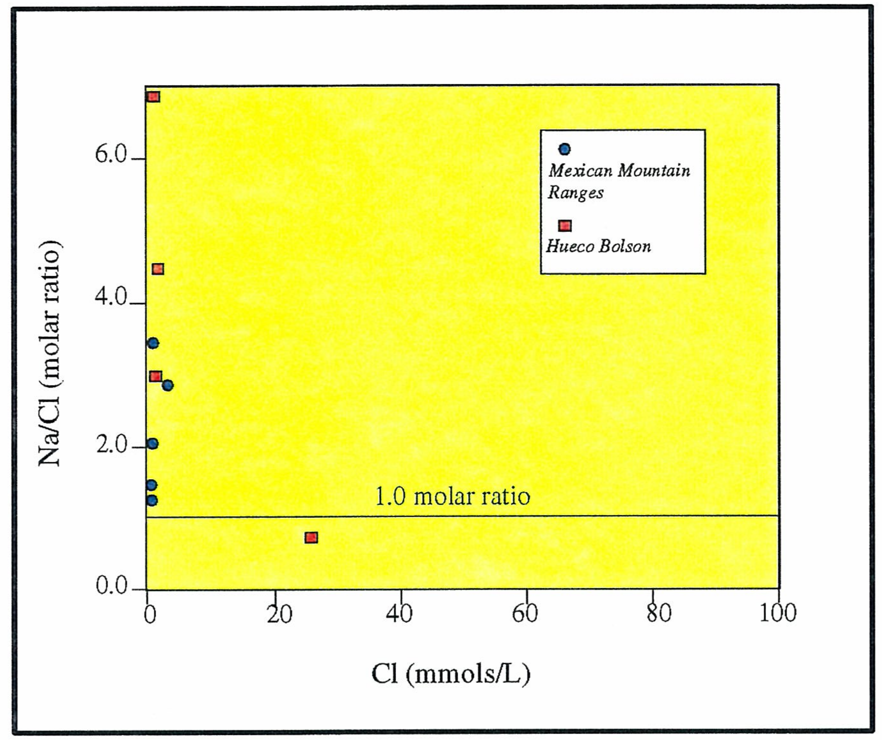

Figure 4.8b. Scatter plot showing (Na/Cl) molar ratios vs molar Cl for samples collected from bedrock strata and bolson strata, Mexico (source of data, Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

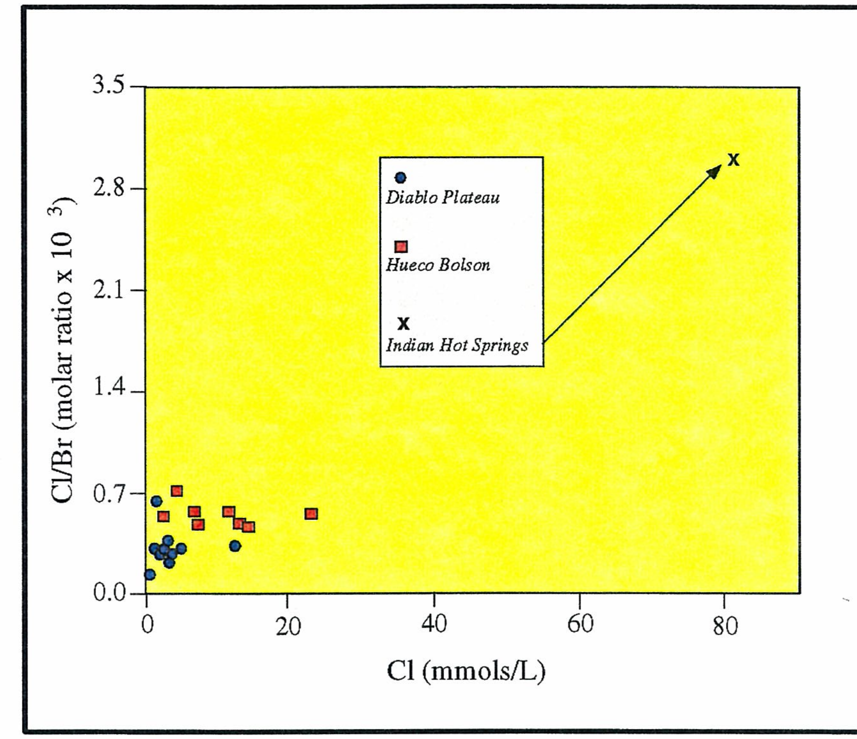

Figure 4.9. Scatter plot showing (Cl/Br) molar ratios vs molar Cl for samples collected from bedrock strata, bolson strata, and Indian Hot Springs, U.S. (source of data, Fisher and Mullican, 1990; Darling and others, 1994; Texas Water Development Board).

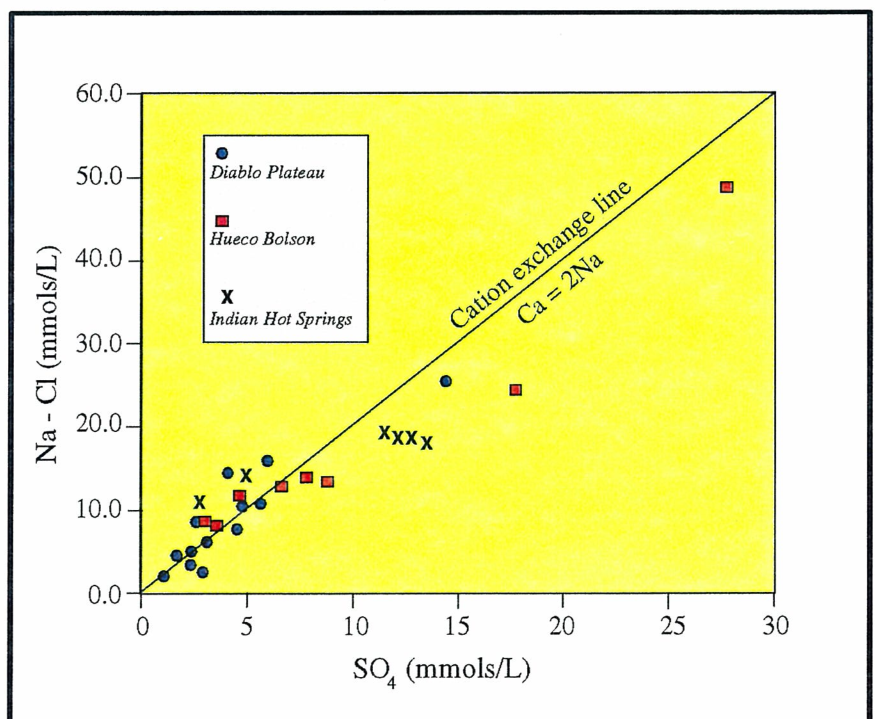

Figure 4.10a. Scatter plot showing (Na - Cl) molar quantity vs molar SO_4 for samples collected from bedrock strata, bolson strata, and Indian Hot Springs, U.S. (source of data, Fisher and Mullican, 1990; Darling and others, 1994; Texas Water Development Board).

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.

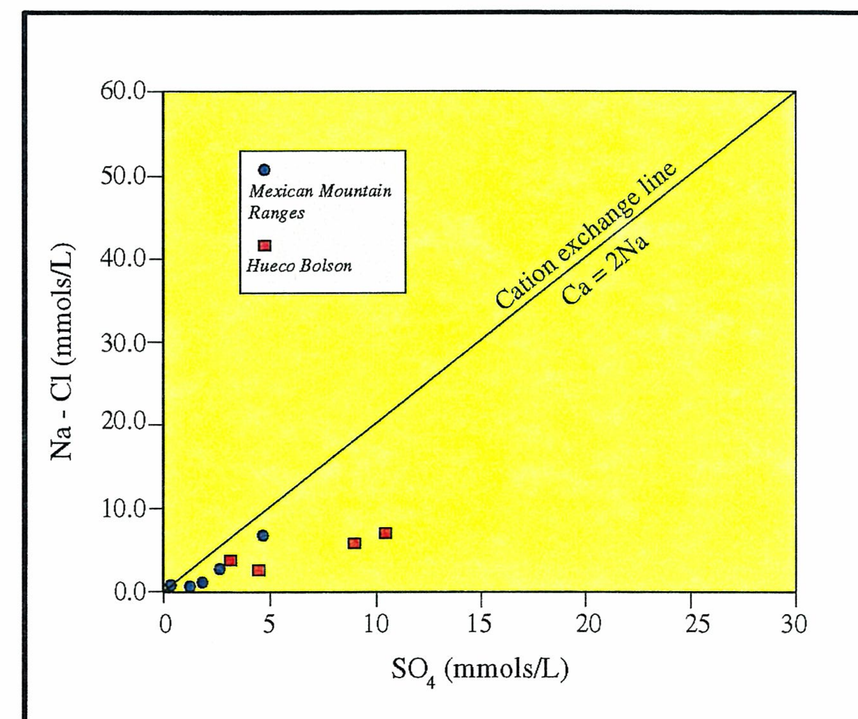

Figure 4.10b. Scatter plot showing (Na - Cl) molar quantity vs molar SO_4 for samples collected from bedrock strata and bolson strata, Mexico (source of data, Comision Nacional Del Agua; Instituto Nacional de Estadistica, Geografia e Informatica).

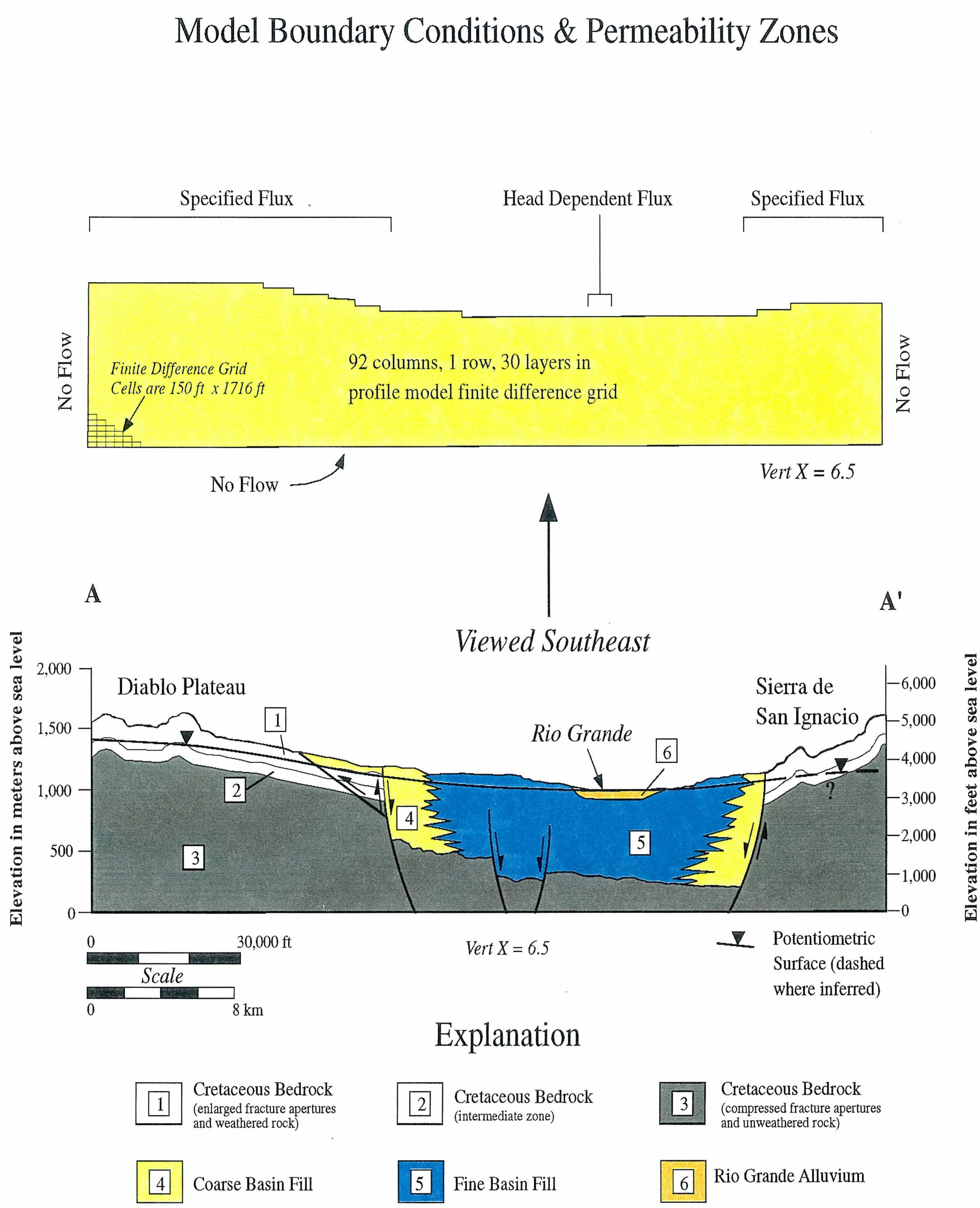

Figure 4.11. Diagram showing the gridding scheme, the aquifer zones, and the boundary conditions selected for the numerical profile model oriented between the Diablo Plateau and the Sierra de San Ignacio (key: zone 1 = Cretaceous rock with enlarged fractures and weathered rock; zone 2 = Cretaceous rock, 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):

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

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

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.

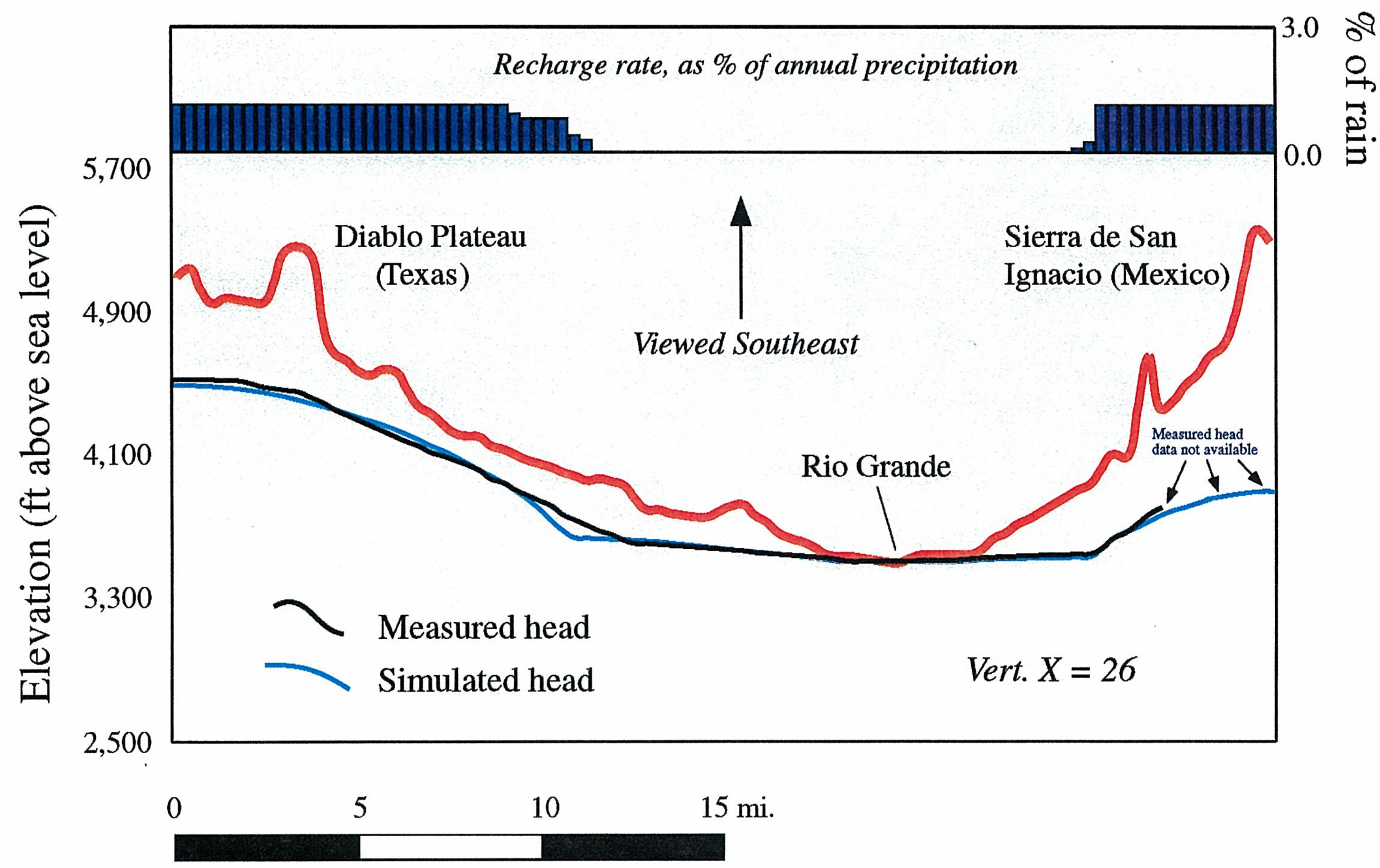

Figure 4.12. Recharge rates and comparison between measured and simulated hydraulic heads in the transboundary profile model.

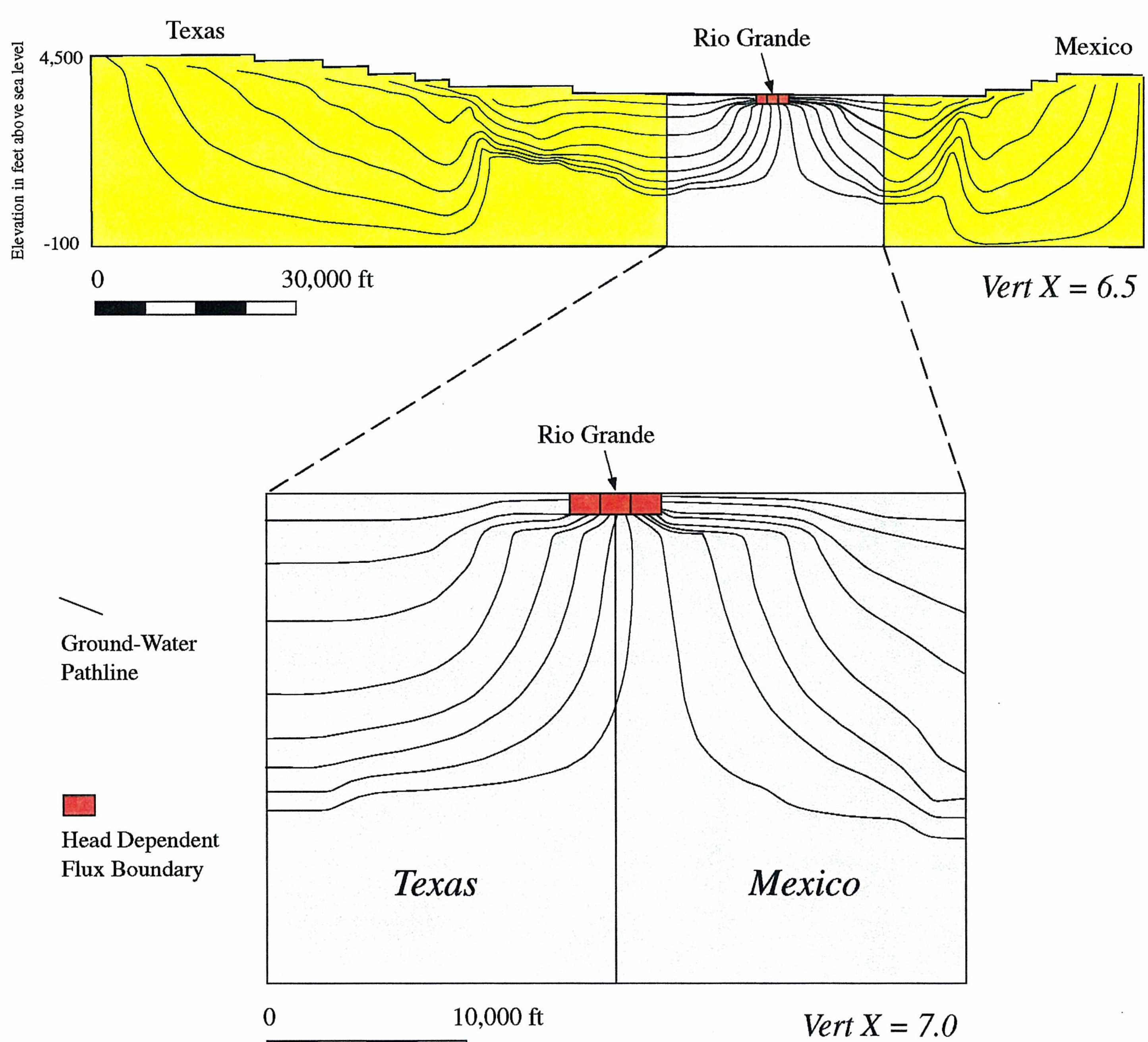

Figure 4.13. Particle trajectories do not form a perfect mirror image where they upwell beneath the international boundary. Pathlines suggest movement of ground water slightly southward into Mexico.

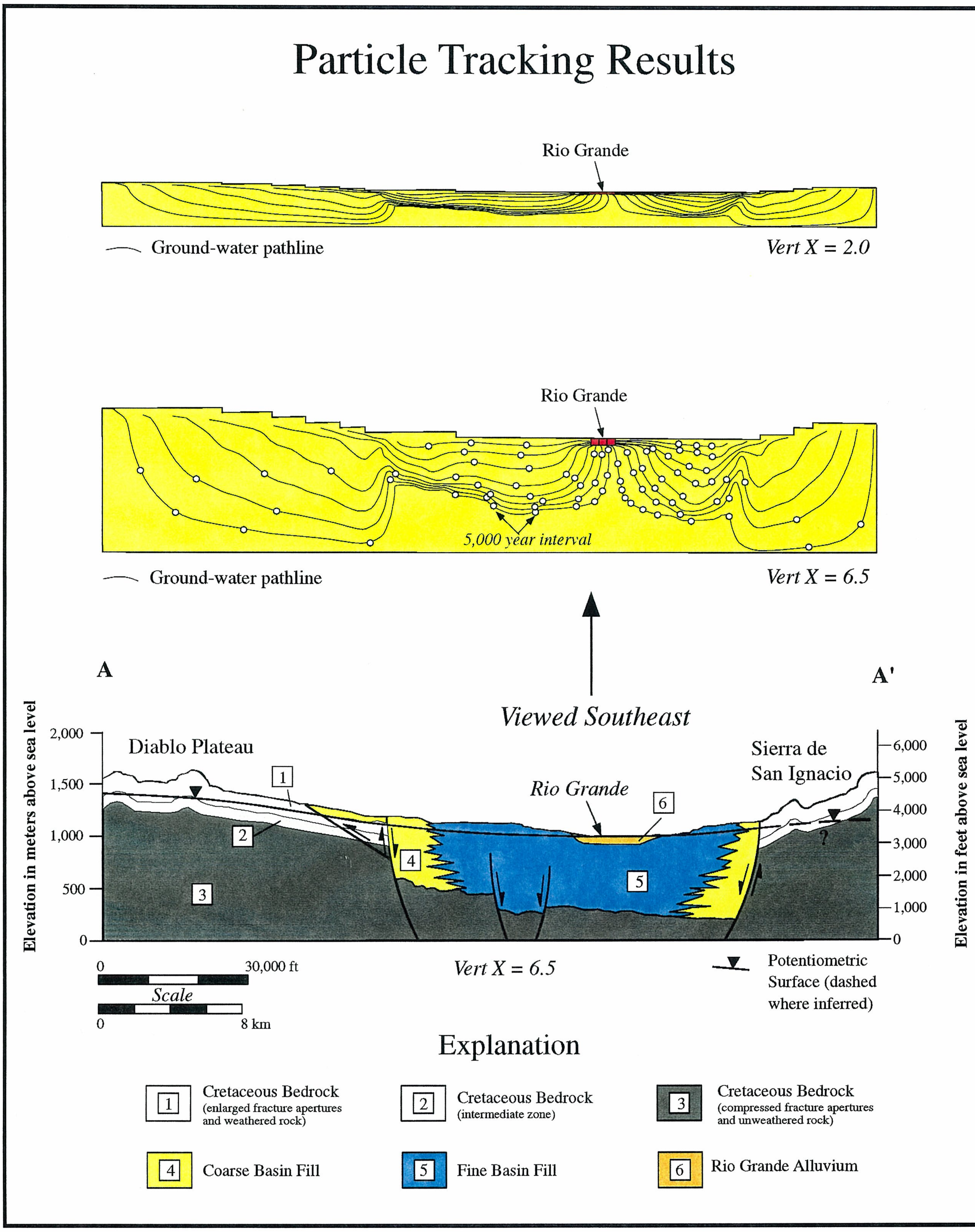

Figure 4.14. Simulated pathlines in the numerical profile model. Alluvial fans act as convergence zones for both short and long pathlines. Pathlines marked by 5,000 year travel times (squares) at segments along the pathline.

(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 ground-water 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.

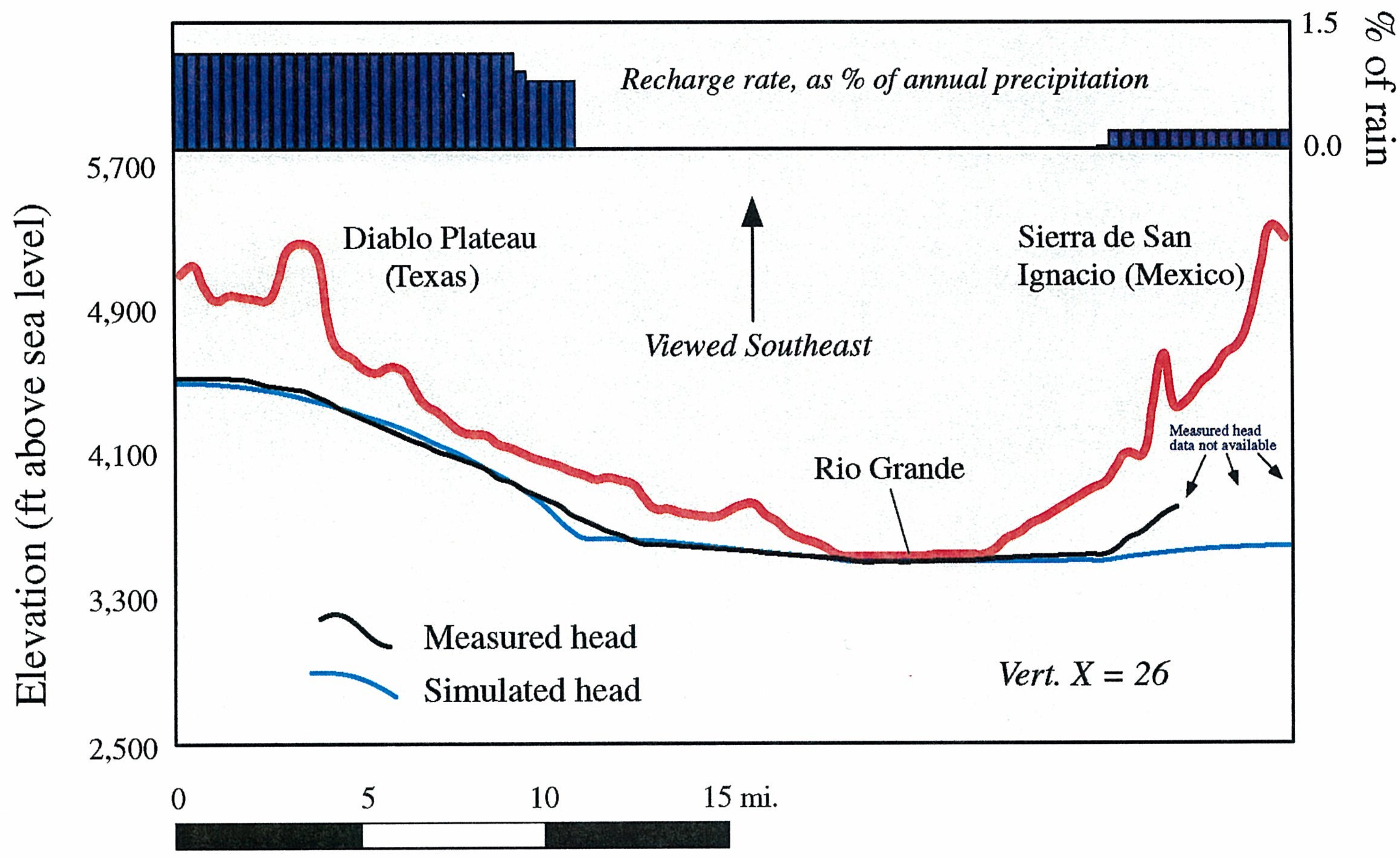

Figure 4.15. Recharge rates and comparison between measured and simulated hydraulic heads in model scenario 1. Prescribed recharge rates are much higher in the United States.

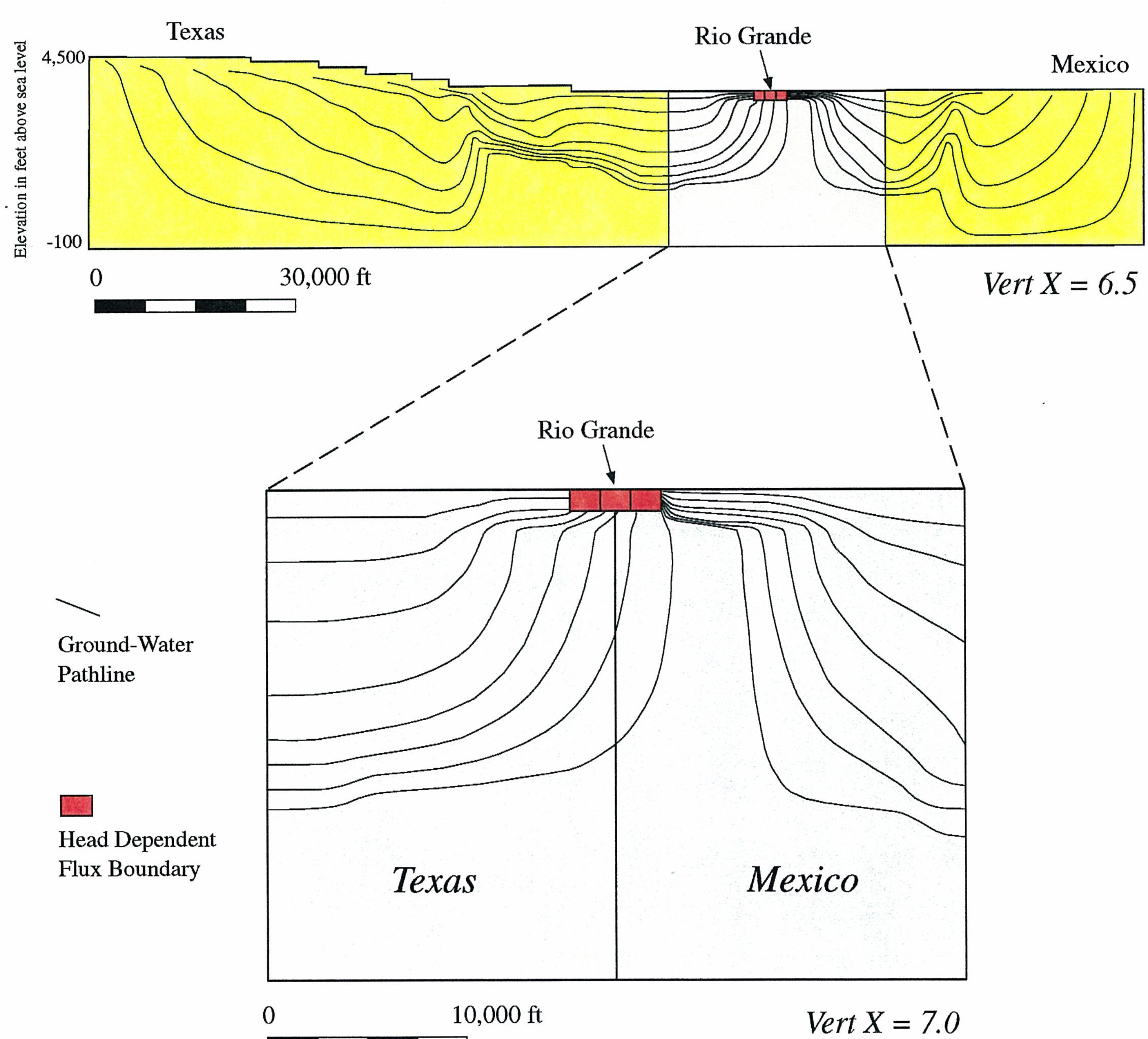

Figure 4.16. Pathlines suggest greater movement of ground water into Mexico with lower recharge rates in the Sierra de San Ignacio, model scenario 1.

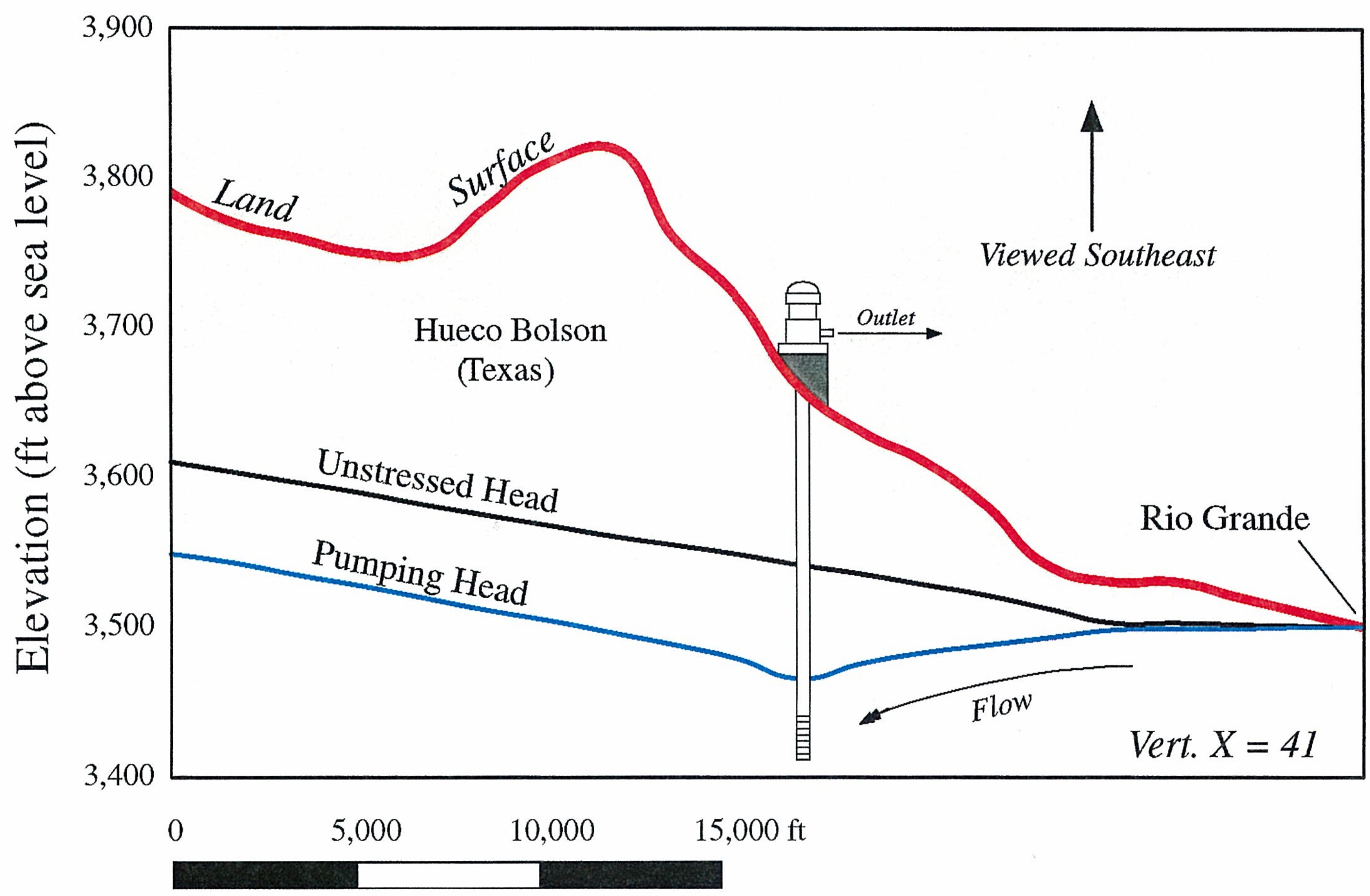

Figure 4.17. Comparison of unstressed hydraulic head and pumping hydraulic head in the numerical profile model, model scenario 2. Pumping cones of depression lower hydraulic head in the Hueco Bolson and induce infiltration of surface water from the Rio Grande.

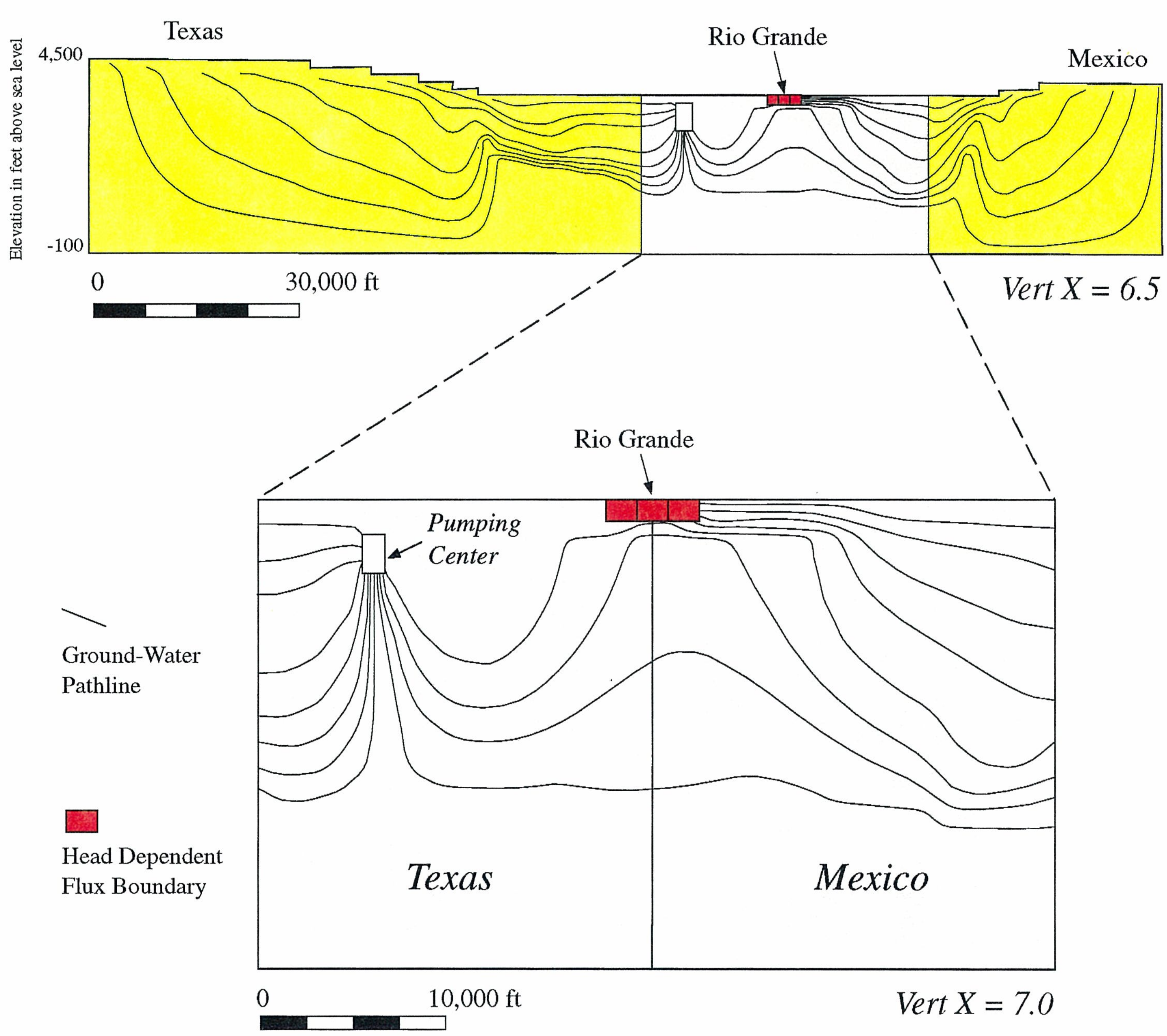

Figure 4.18. Pathlines originating in Mexico move across the international border to pumping cones of depression in the Texas portion of the southeastern Hueco Bolson in model scenario 2.

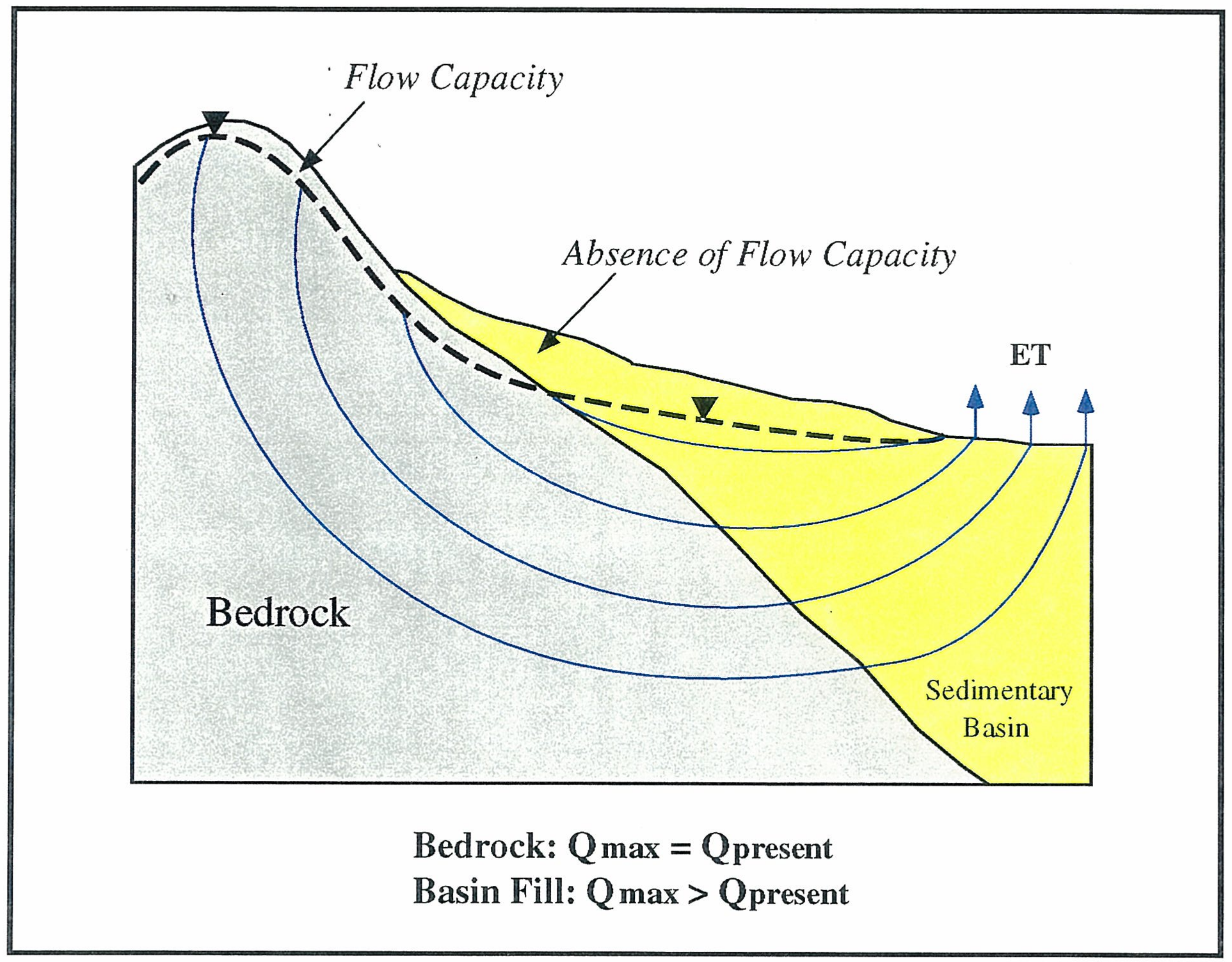

Figure 4.19a. Diagram showing flow capacity in the highland bedrock aquifer and absence of flow capacity in the sedimentary basin aquifer (modified from Mifflin, 1968).

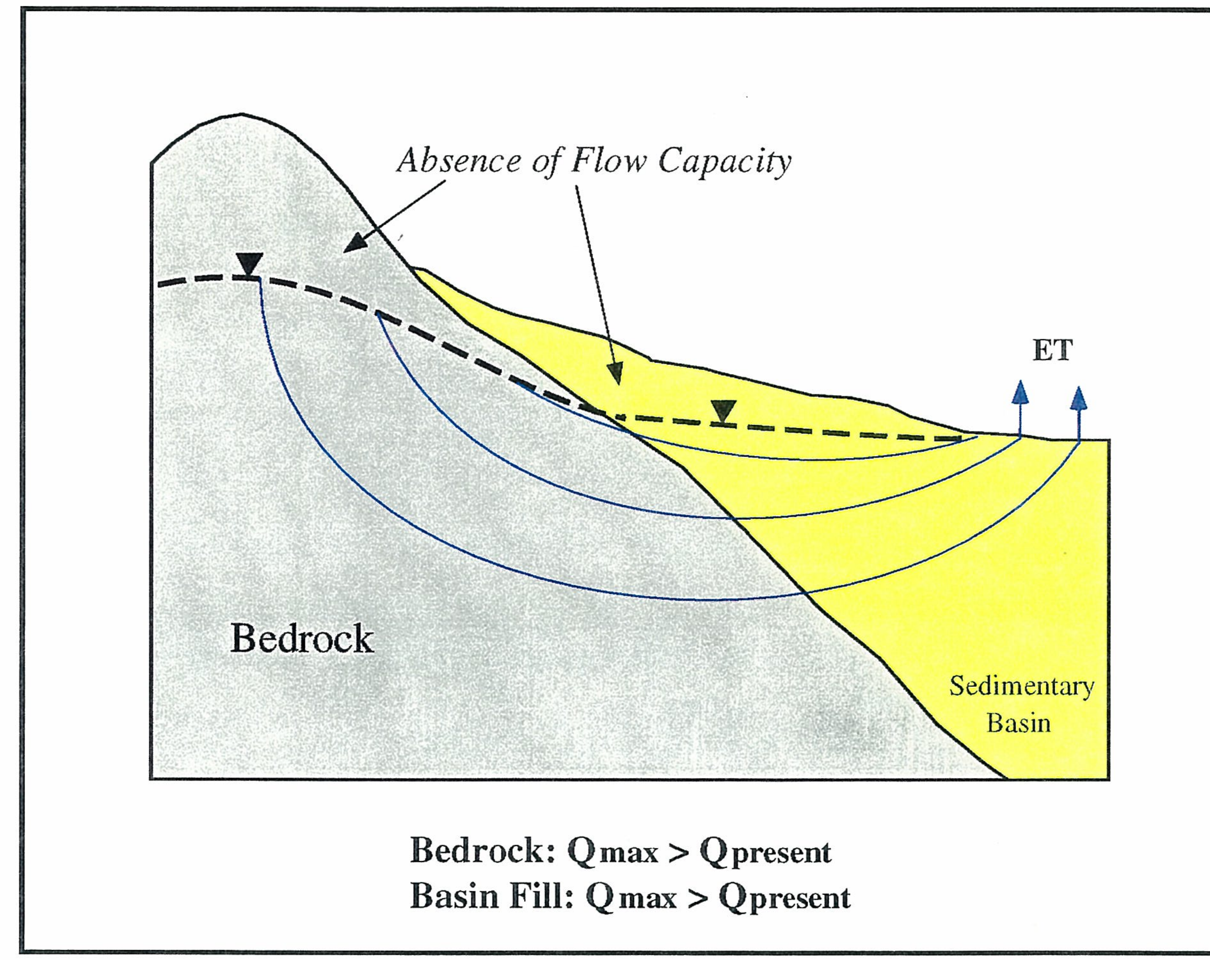

Figure 4.19b. Diagram showing absence of flow capacity in the bedrock and basin aquifers. Mountains in desert basins are typically not at flow capacity (modified from Mifflin, 1968).

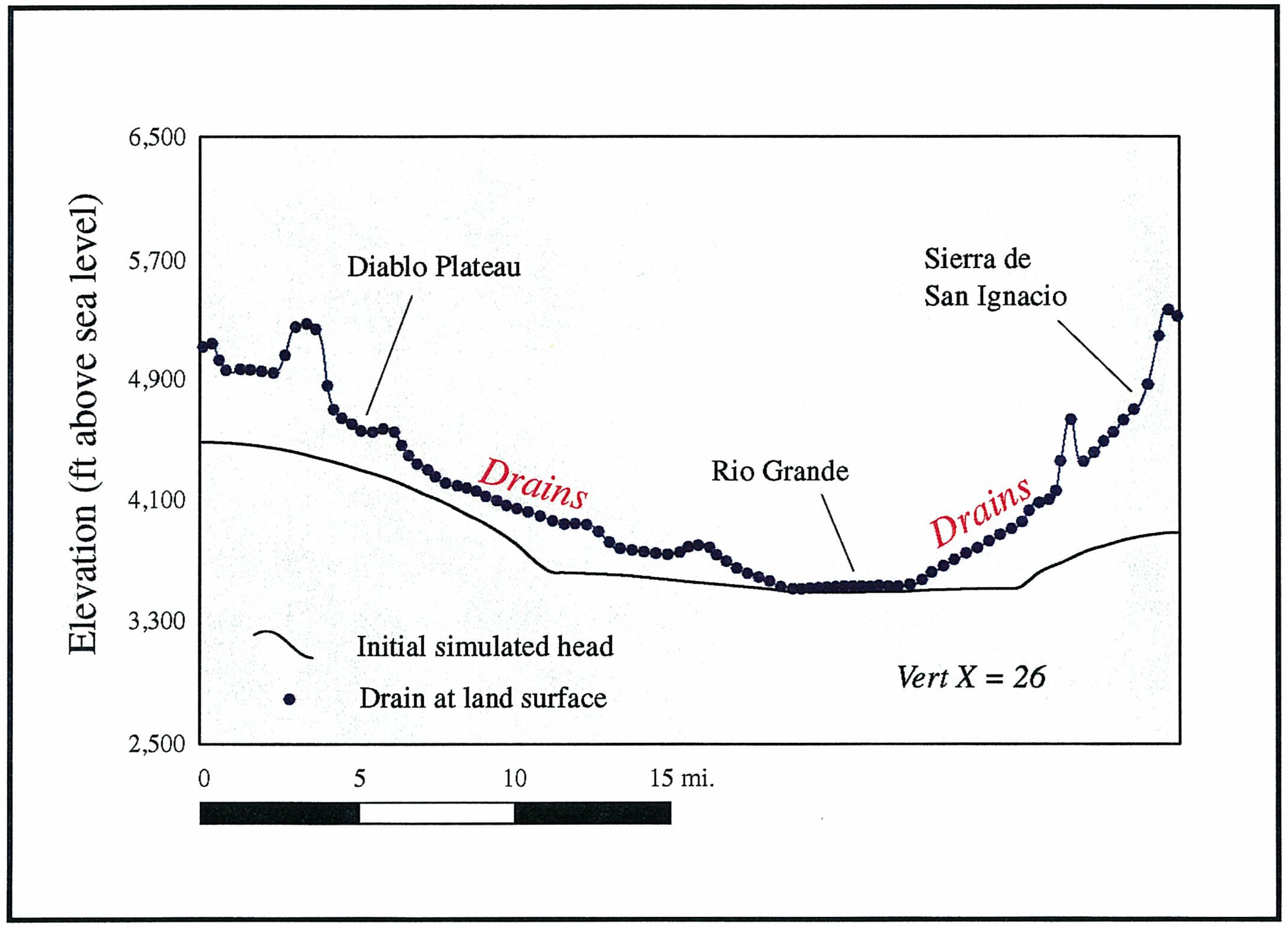

Figure 4.20. Drains specified at land surface elevation in the numerical profile model, model scenario 3.

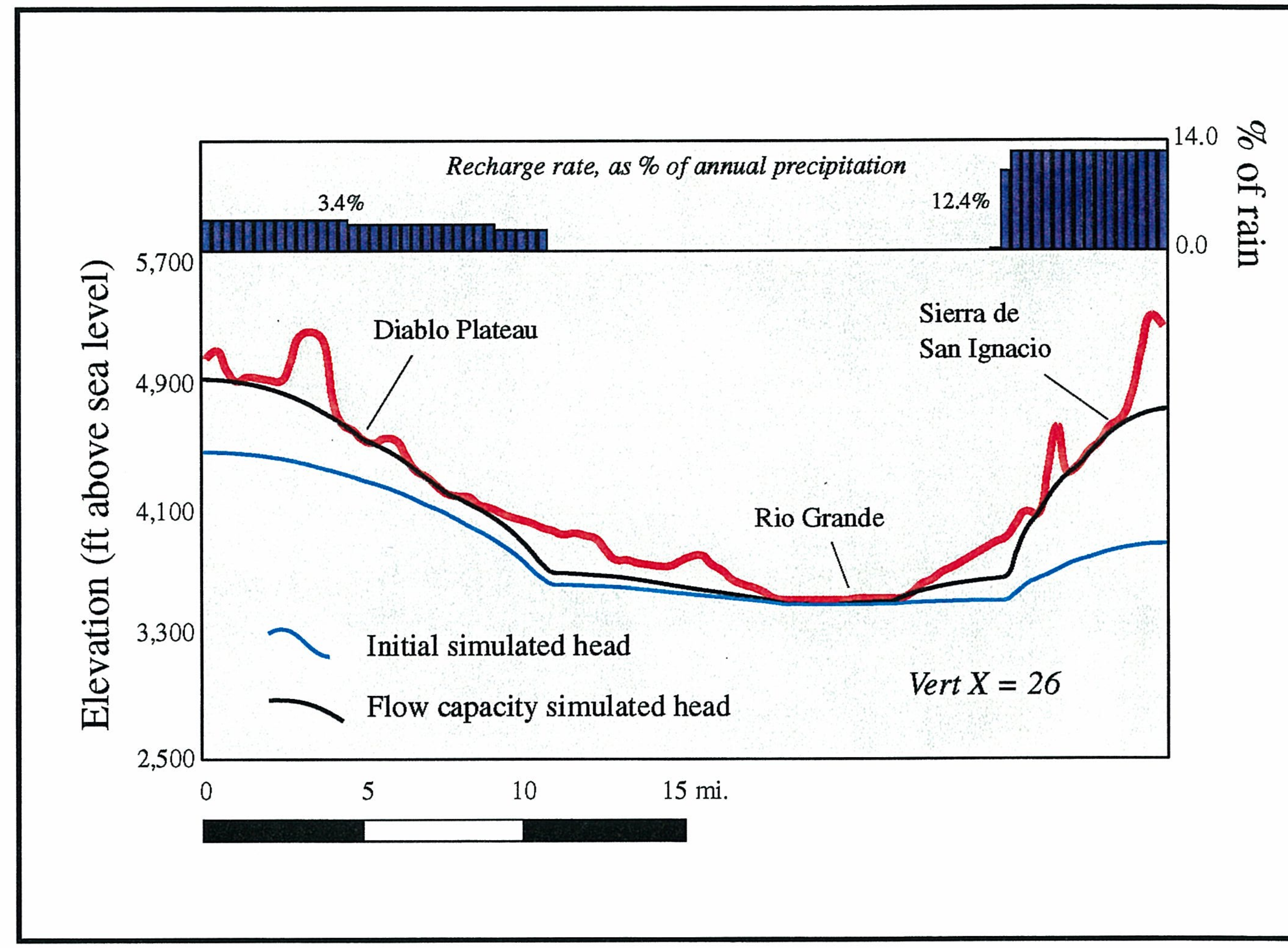

Figure 4.21. Comparison of initial simulated hydraulic head (see Figure 4.12) and simulated hydraulic head at flow capacity; and recharge rates at flow capacity, model scenario 3.

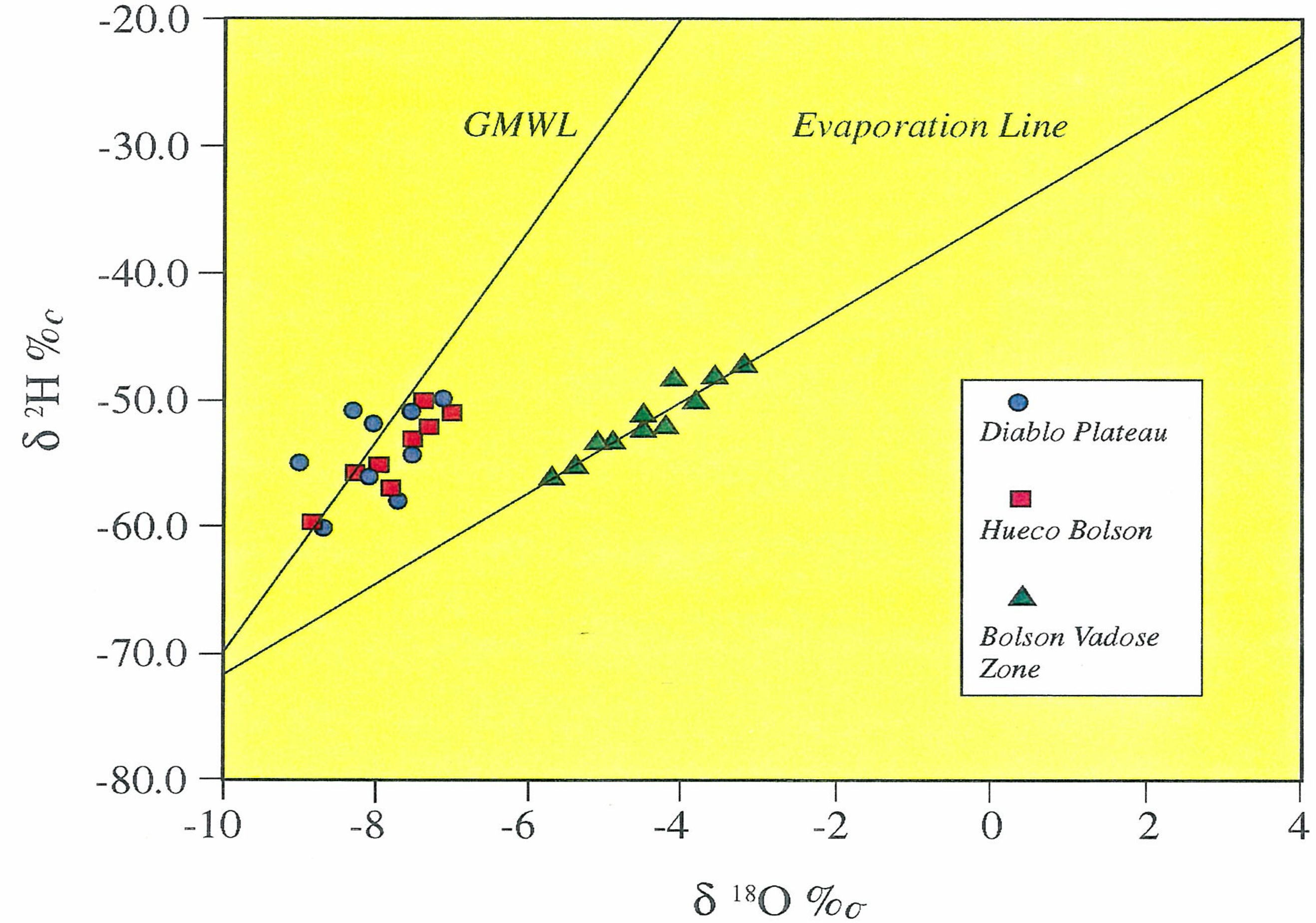

Figure 4.22. Binary plot of δ^2H versus δ^{18}O values for vadose zone and saturated zone waters in the southeastern Hueco aquifer. Stable hydrogen and oxygen isotope ratios in ground water (Diablo Plateau and Hueco Bolson) plot generally along the global meteoric water line (GMWL), indicating little 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).

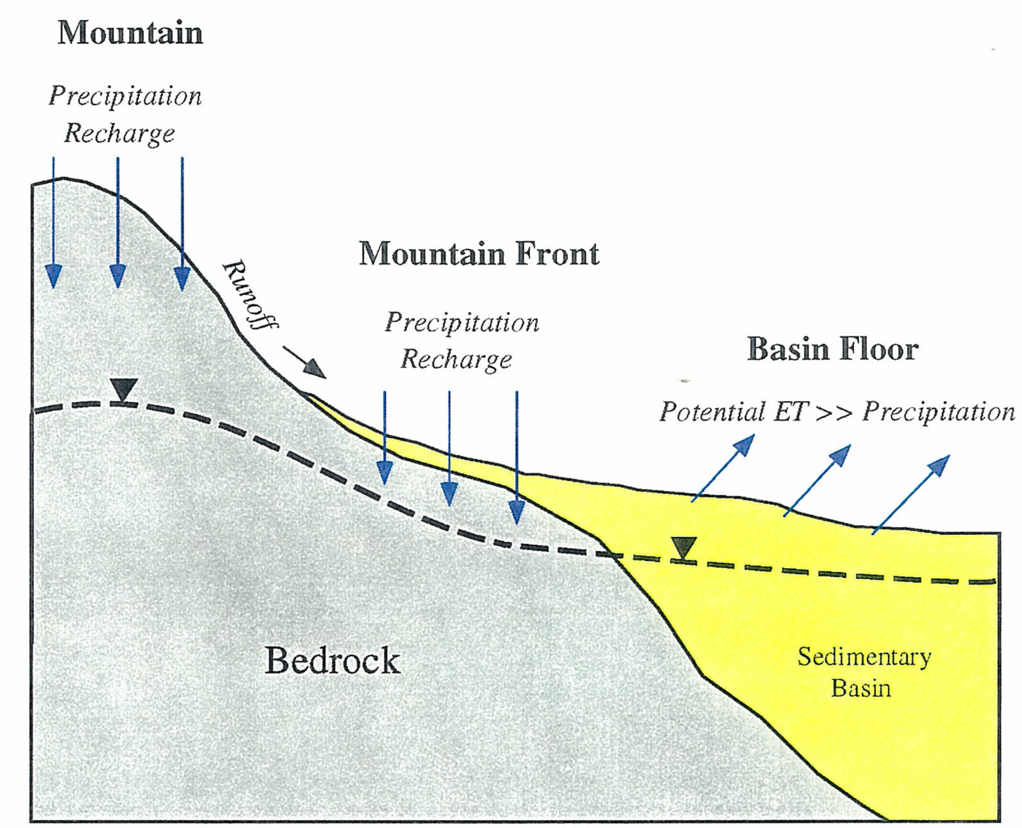

Figure 4.23. Conceptual model showing mountain and mountain front recharge and the absence of precipitation recharge along the basin floor due to the substantial excess of evapotranspiration over precipitation.

- 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

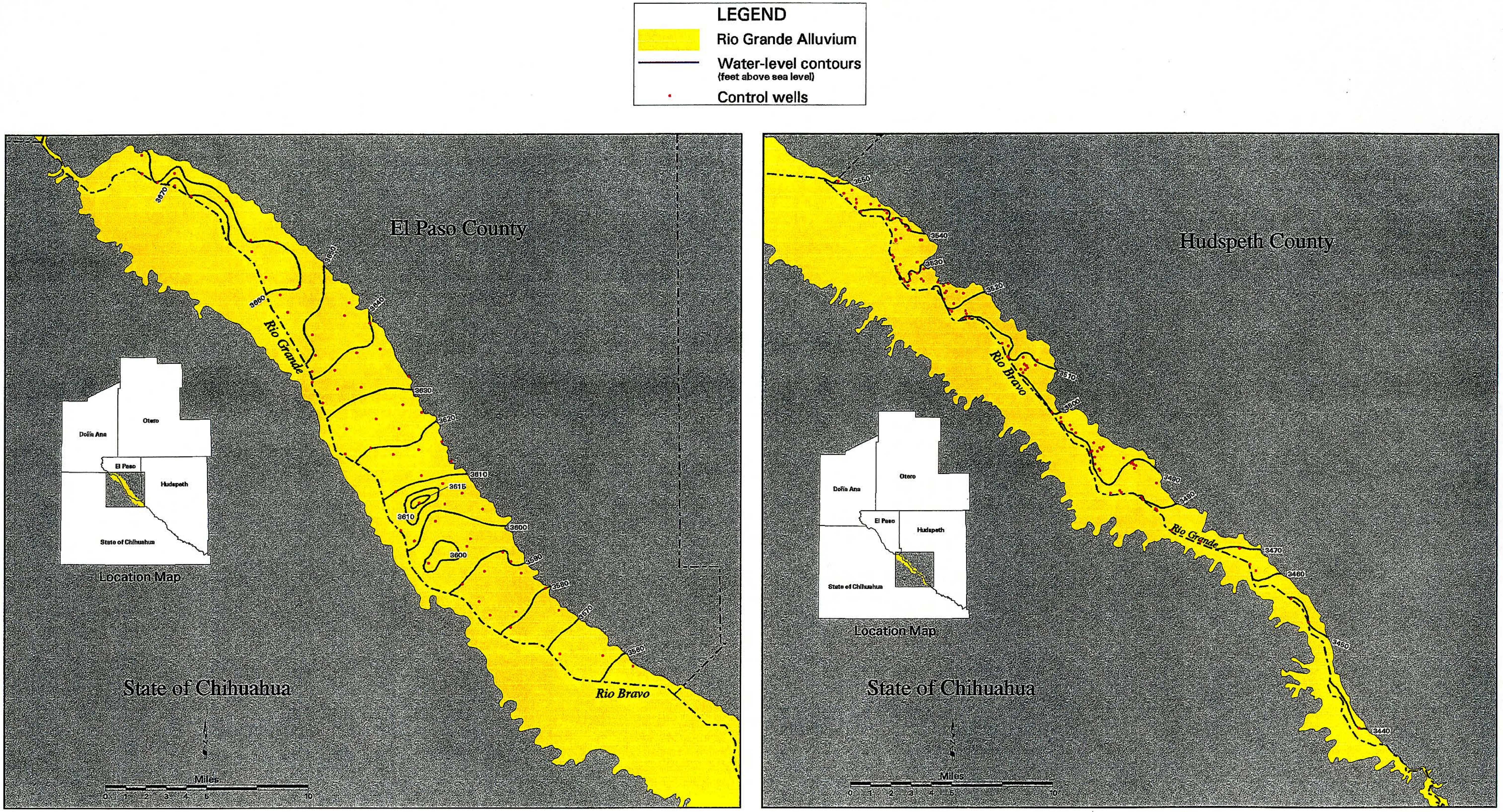


Figure 5.2. Water level contour map for the Rio Grande aquifer in El Paso and Hudspeth Counties, 1973 and 1974. Map illustrates losing stream, underflow, and baseflow conditions at different segments of the floodplain (source of data, Texas Water Development Board).

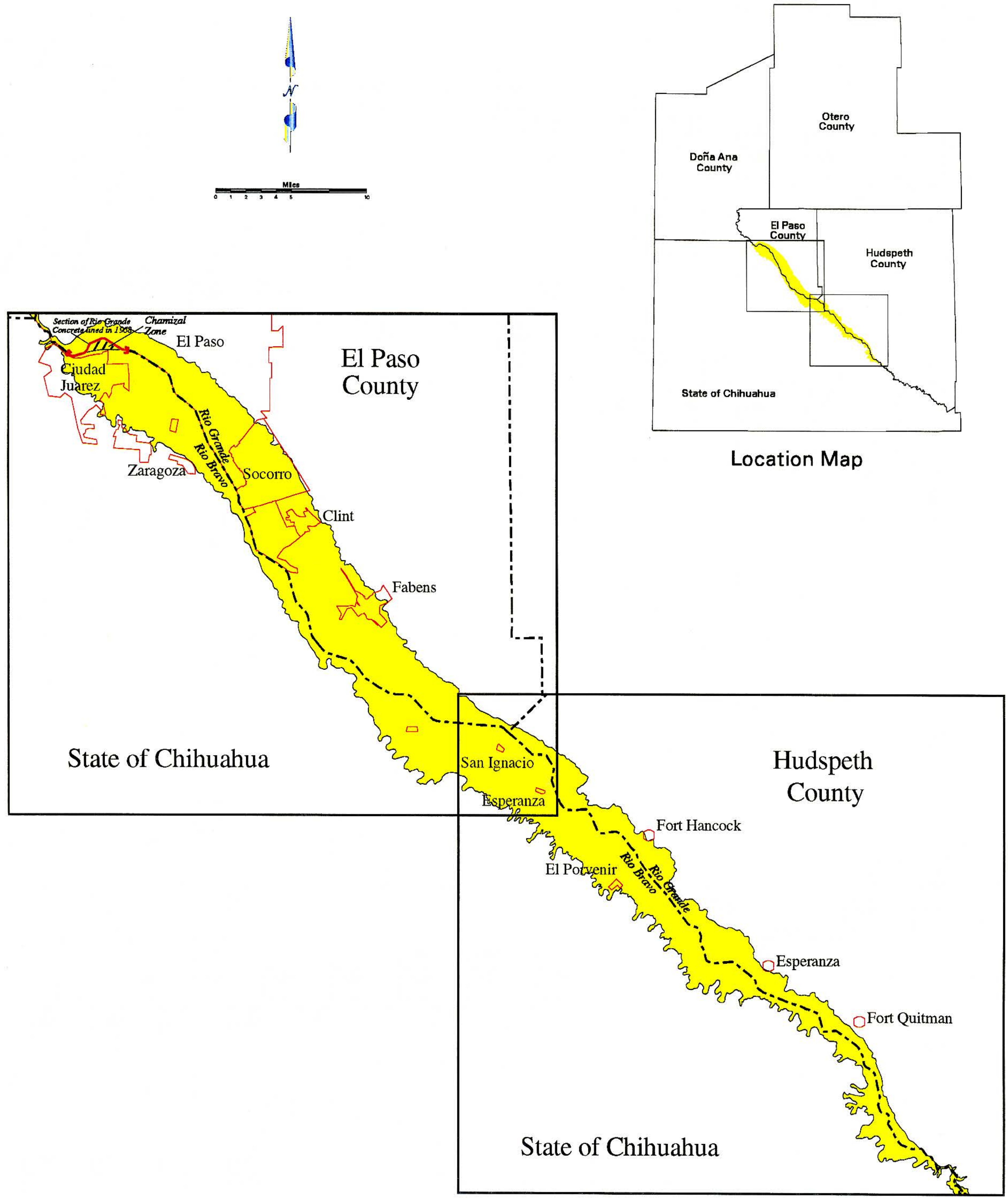


Figure 5.1. Location of the Rio Grande aquifer in the study area

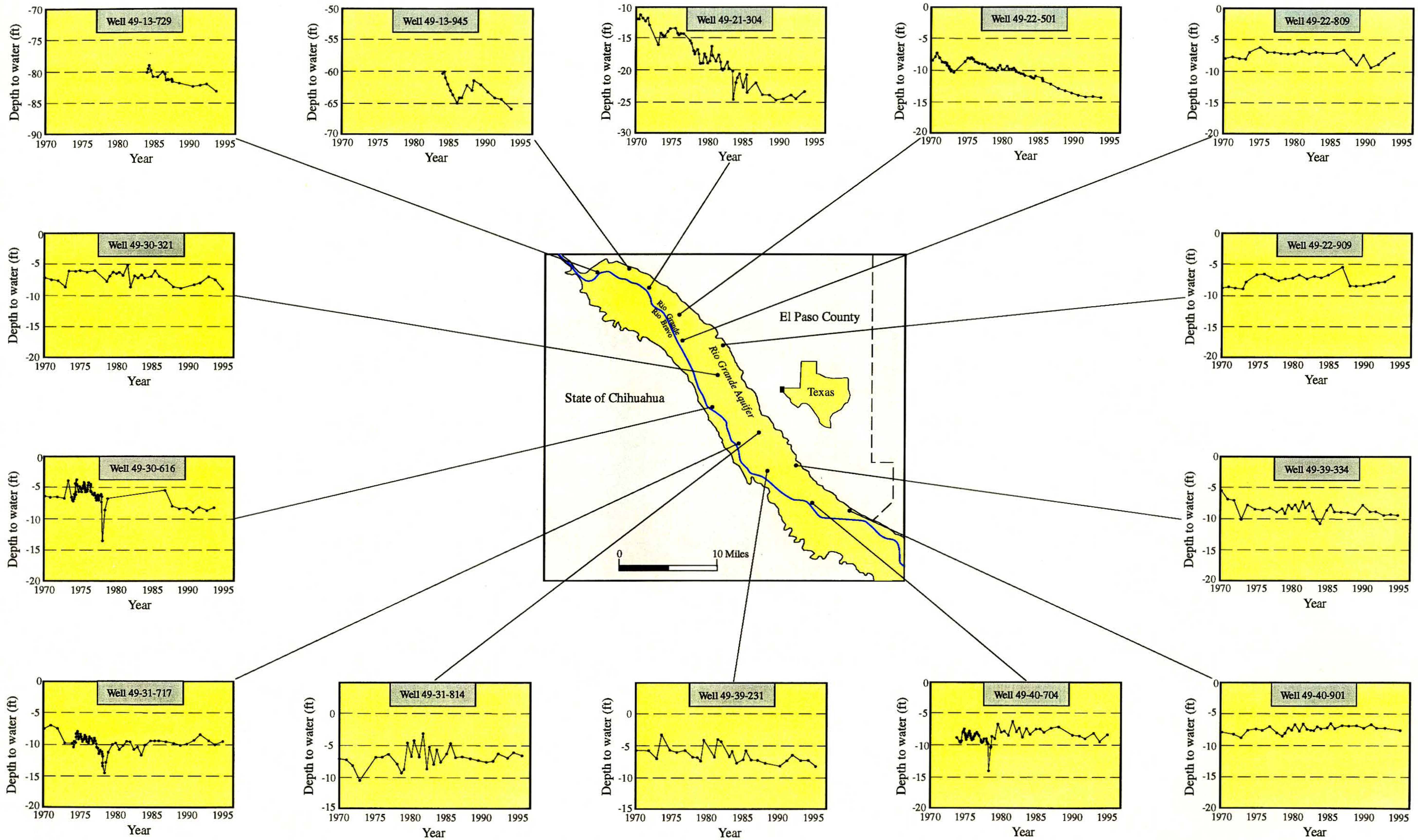


Figure 5.5. Hydrographs illustrating water-level changes in the Rio Grande aquifer in El Paso County between 1970 and 1995 (source of data; Texas Water Development Board).

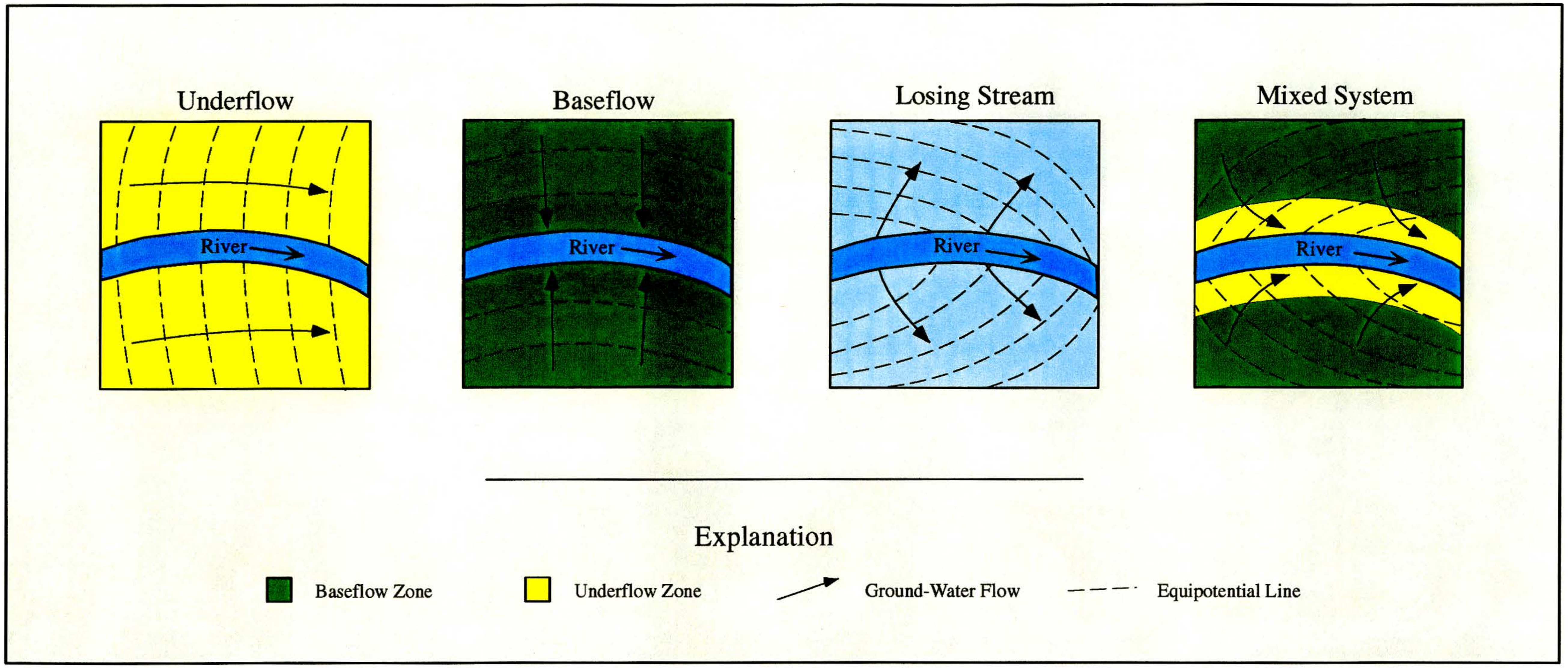


Figure 5.4. Diagram illustrating underflow, baseflow, losing stream, and a mixed system that includes underflow and baseflow components of flow in an alluvial aquifer hydraulically connected to a river (modified from Larkin, 1988).

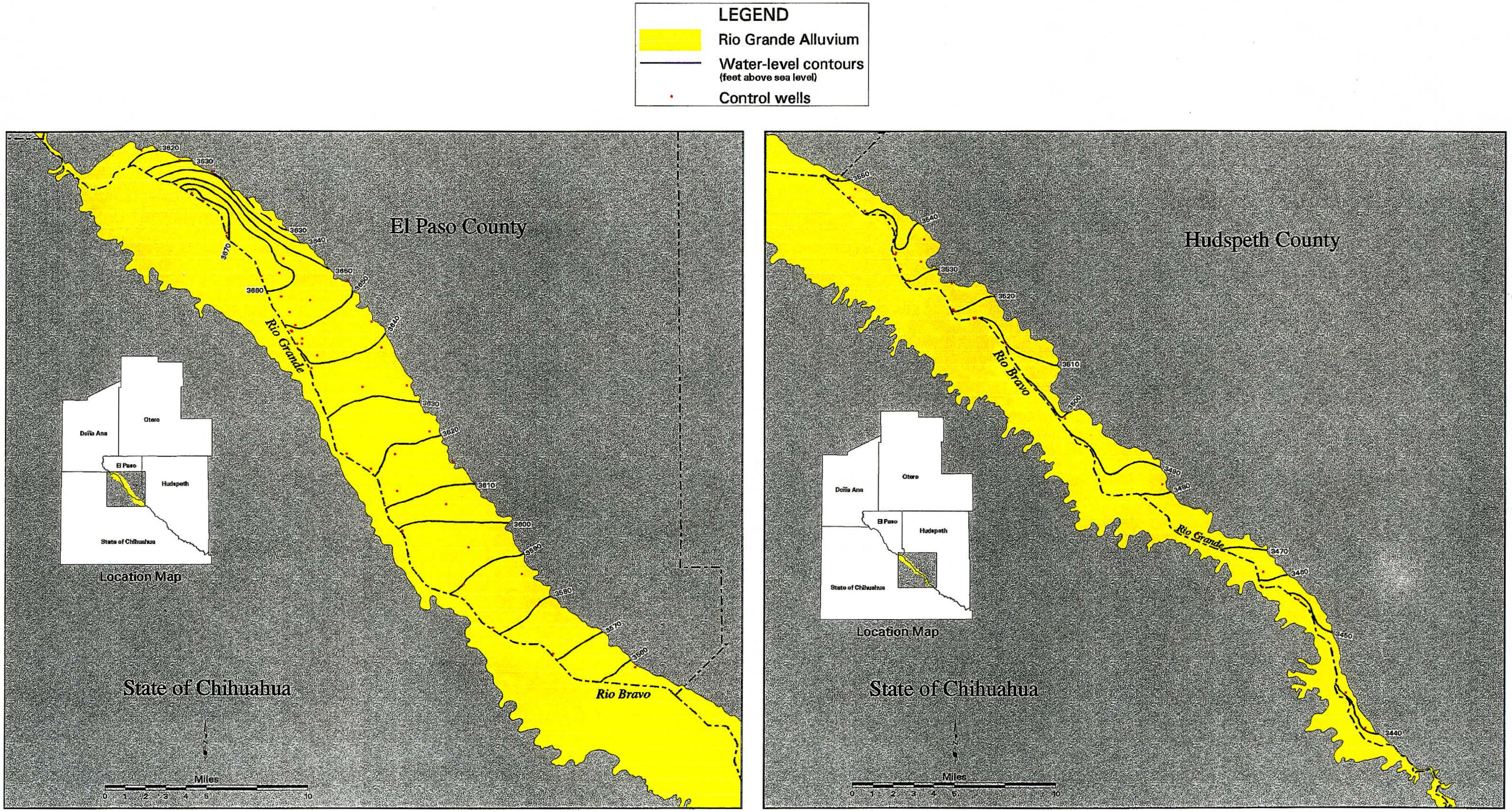


Figure 5.3. Water level contour map for the Rio Grande aquifer in El Paso and Hudspeth Counties, 1994 and 1995. A comparison of figures 5.2 and 5.3 indicates that drawdowns have intensified in the El Paso area since 1973 (see figure 5.1 for delineation of the El Paso area. Source of data, Texas Water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

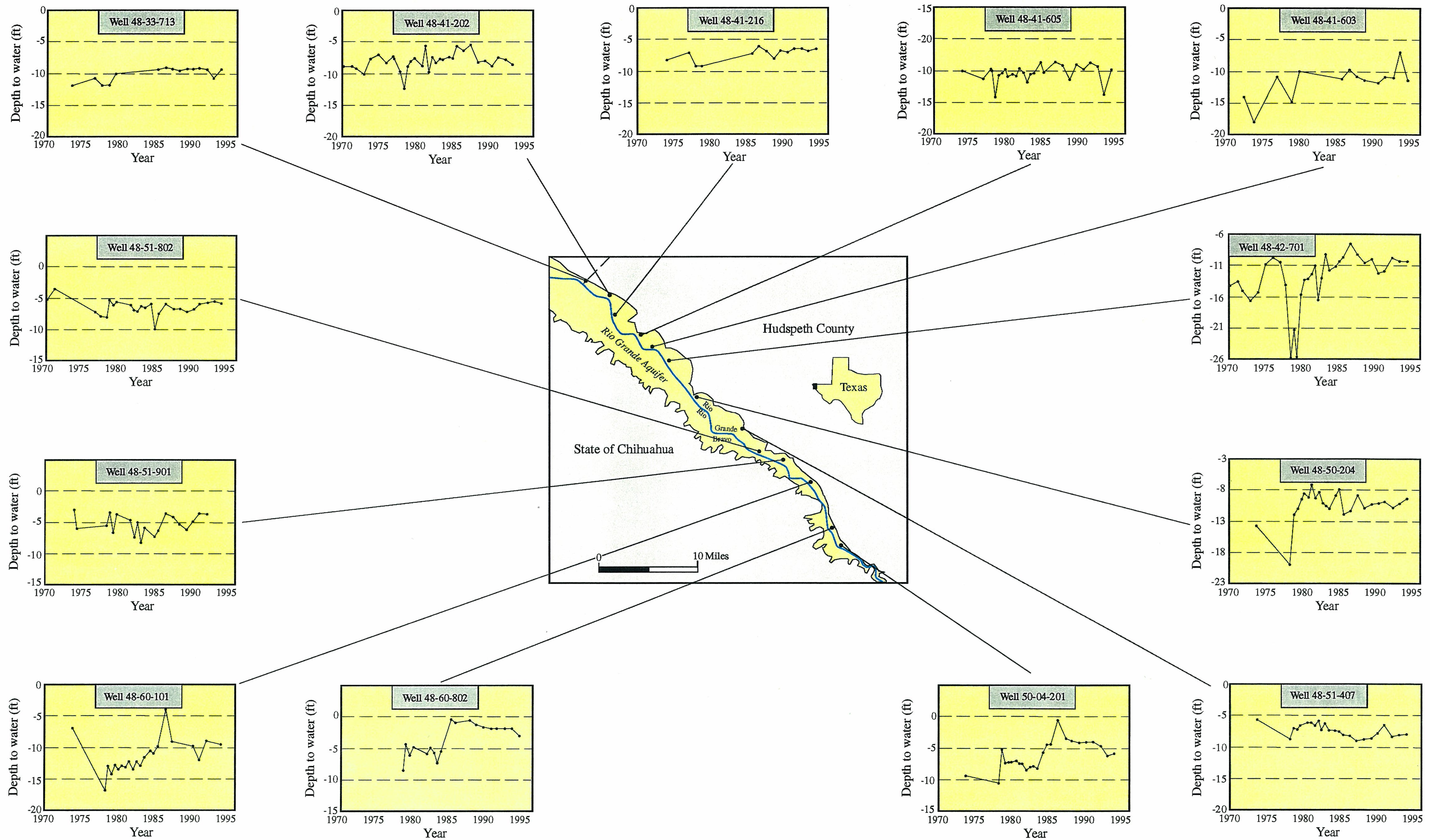


Figure 5.6. Hydrographs illustrating water-level changes in the Rio Grande aquifer in Hudspeth County between 1970 and 1995 (source of data; Texas Water Development Board).

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-

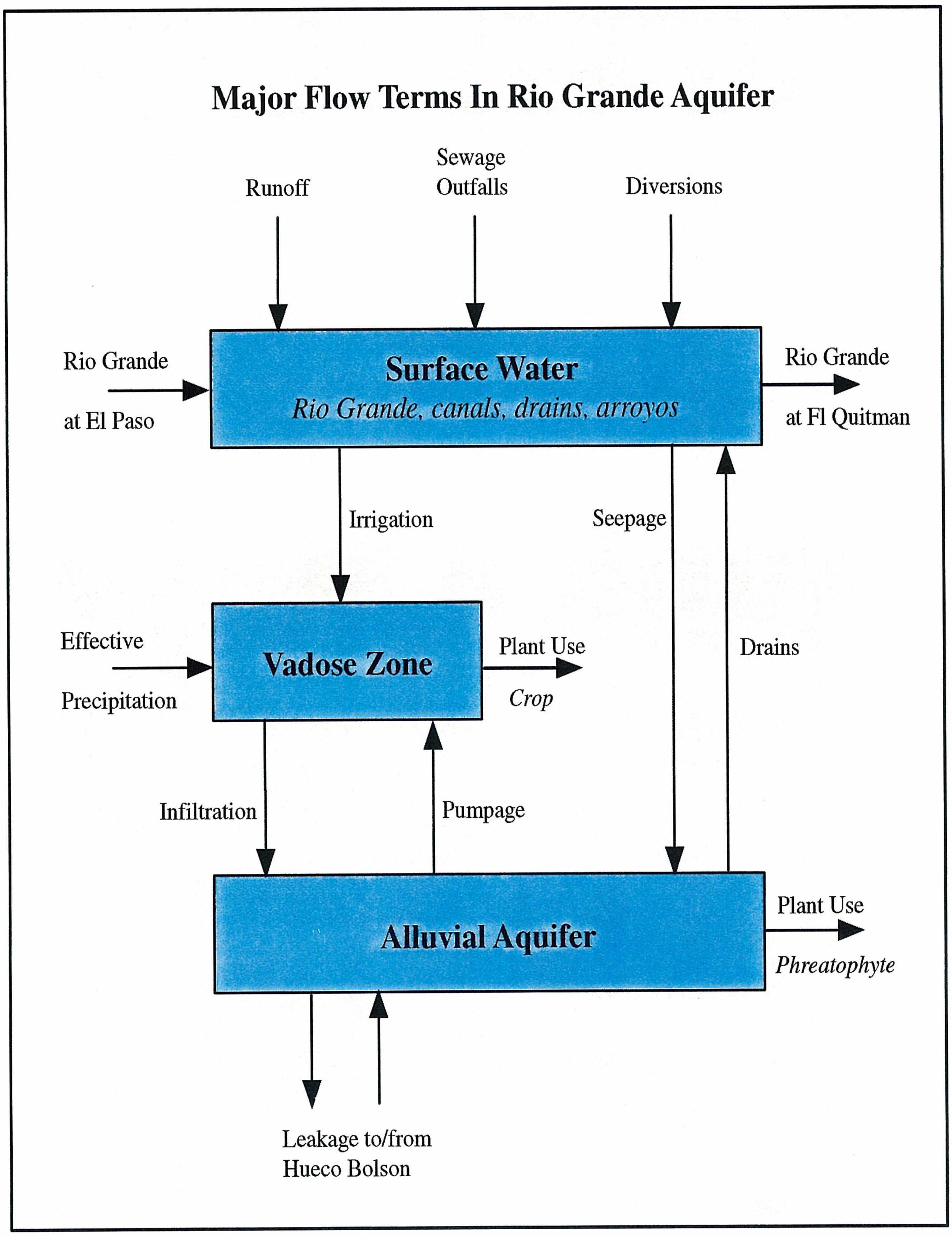


Figure 5.7. Major flow components in the Rio Grande aquifer.

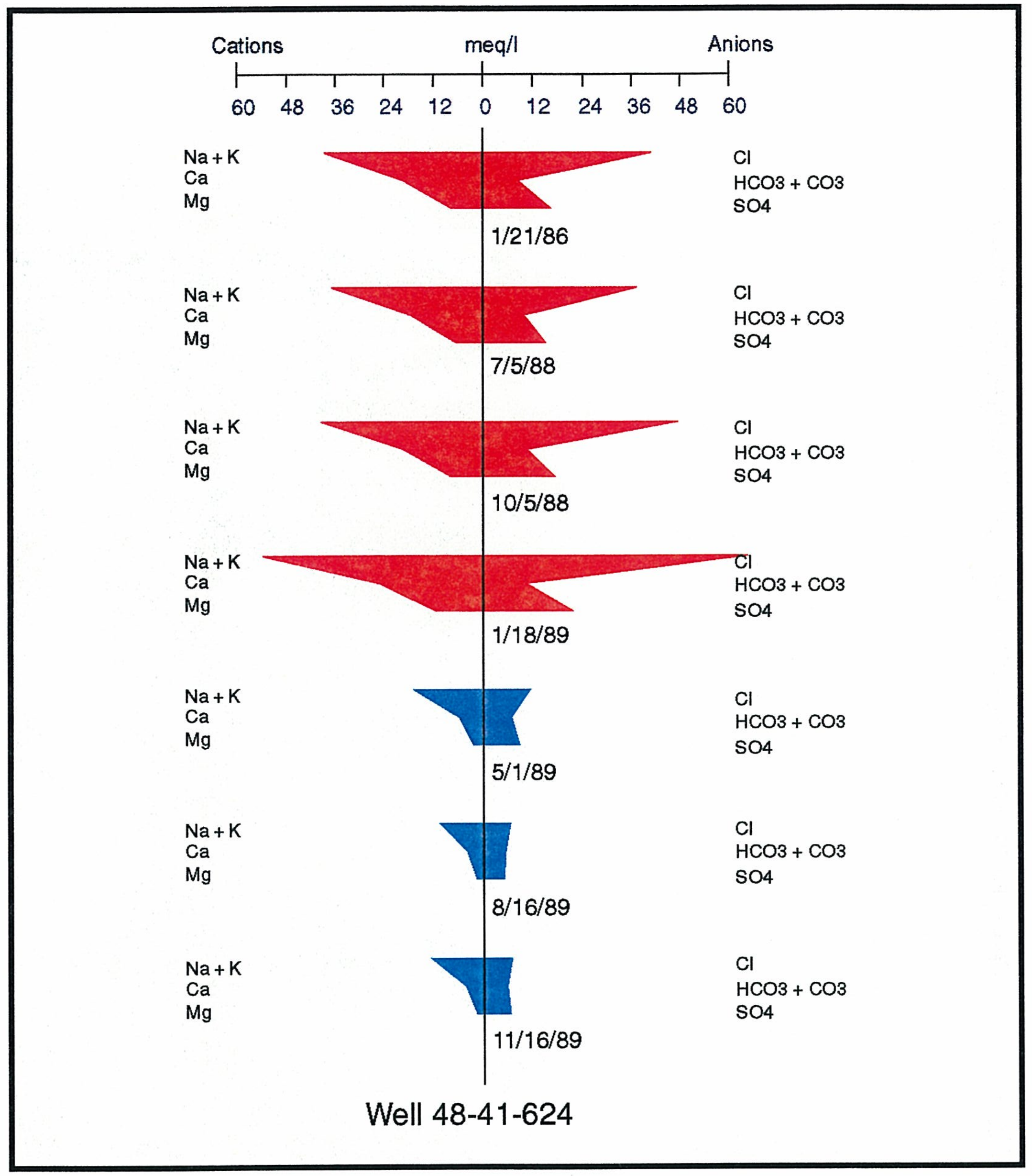


Figure 5.8a. Located adjacent to the Rio Grande, well 48-41-624 had increasing total dissolved solids in samples collected between 1986 and 1989. When the well was resampled in May, 1989, total dissolved solids had decreased substantially (source of data, Texas Water Development Board).

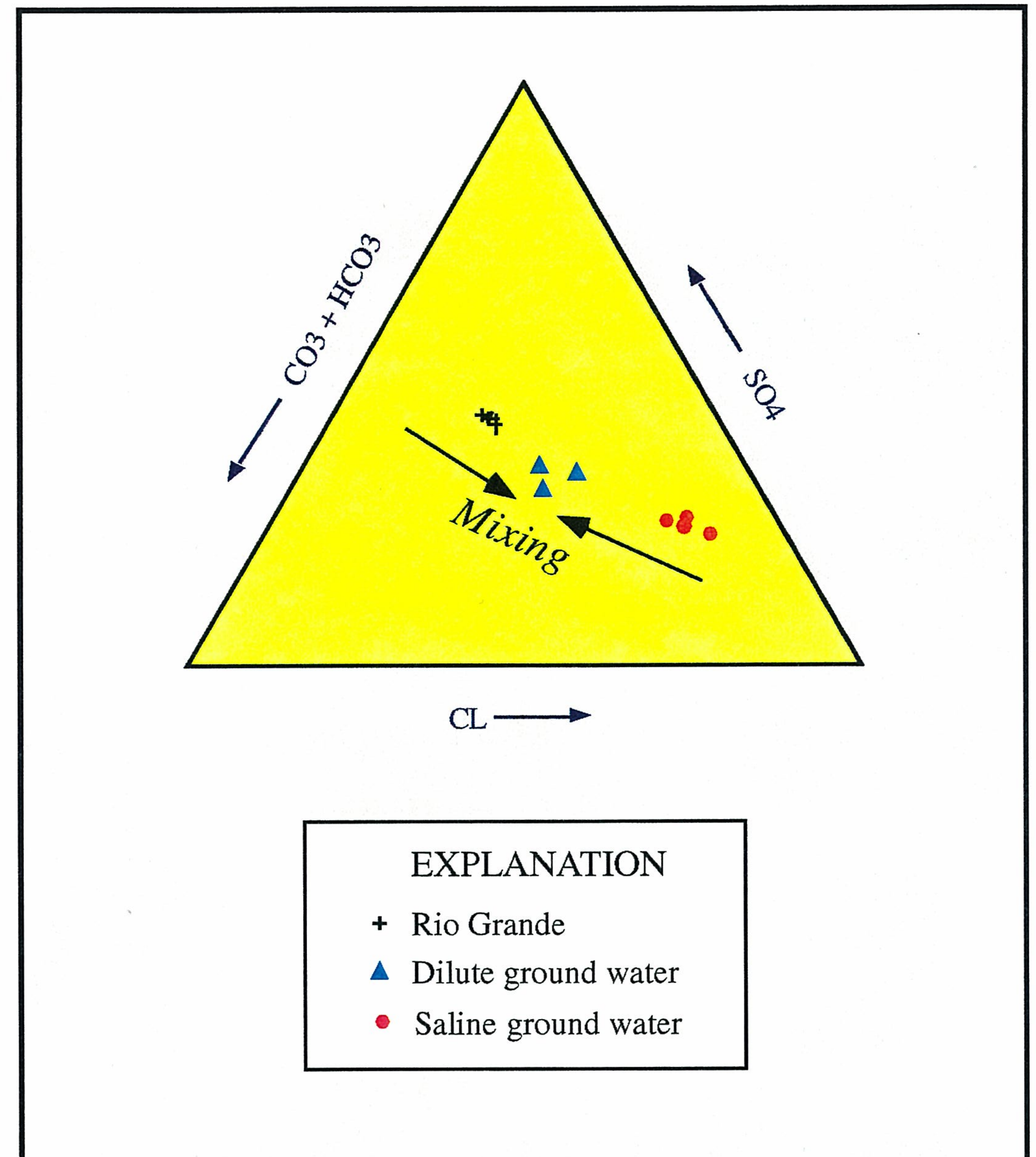
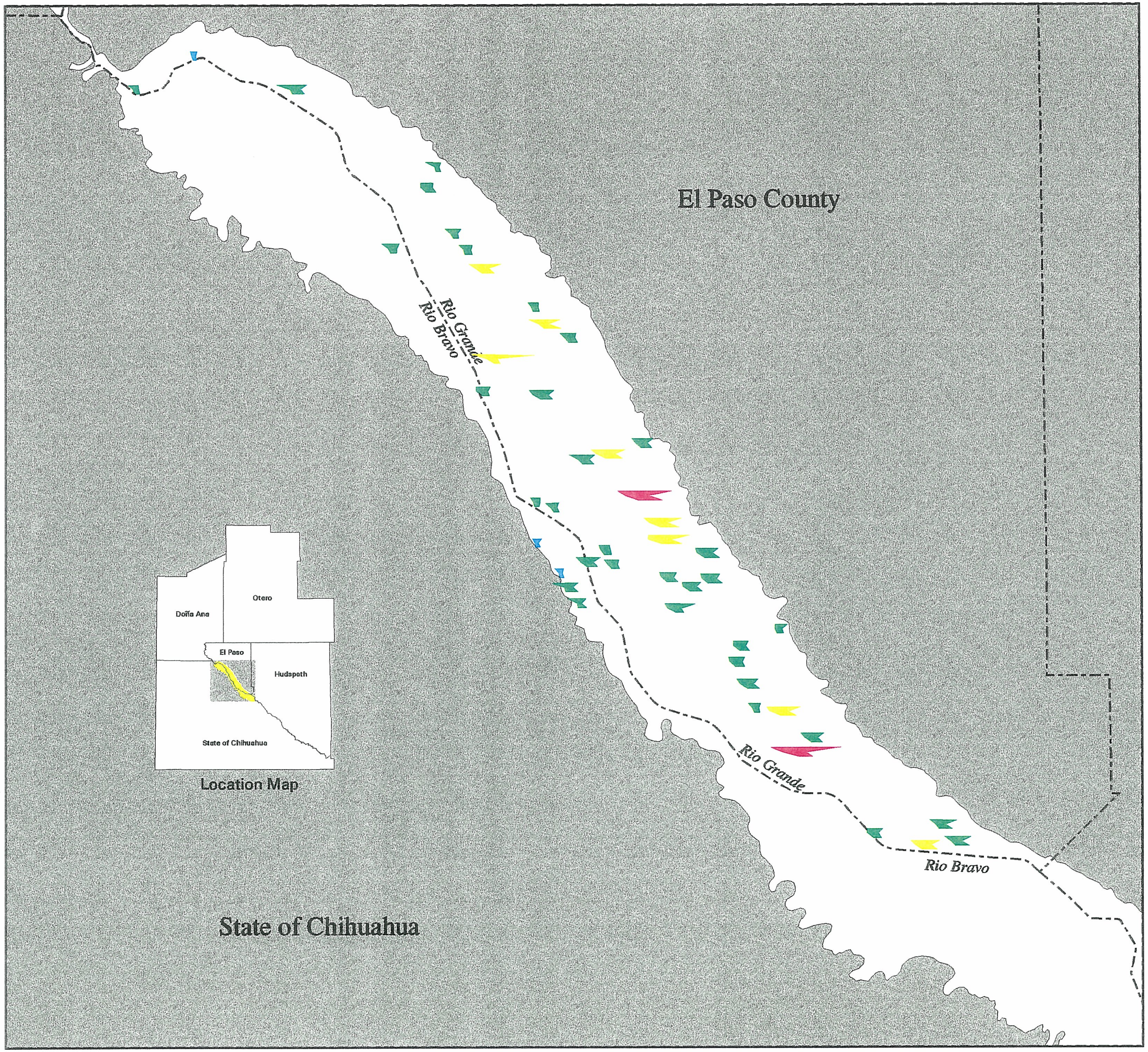


Figure 5.8b. The trilinear plot shows enriched well samples from Figure 5.8a (1986 - 1989), dilute well samples (May, 1989 and later), and Rio Grande samples collected in 1989. Results indicate dilution of ground water due to mixing with Rio Grande water (source of data, Texas Water Development Board).



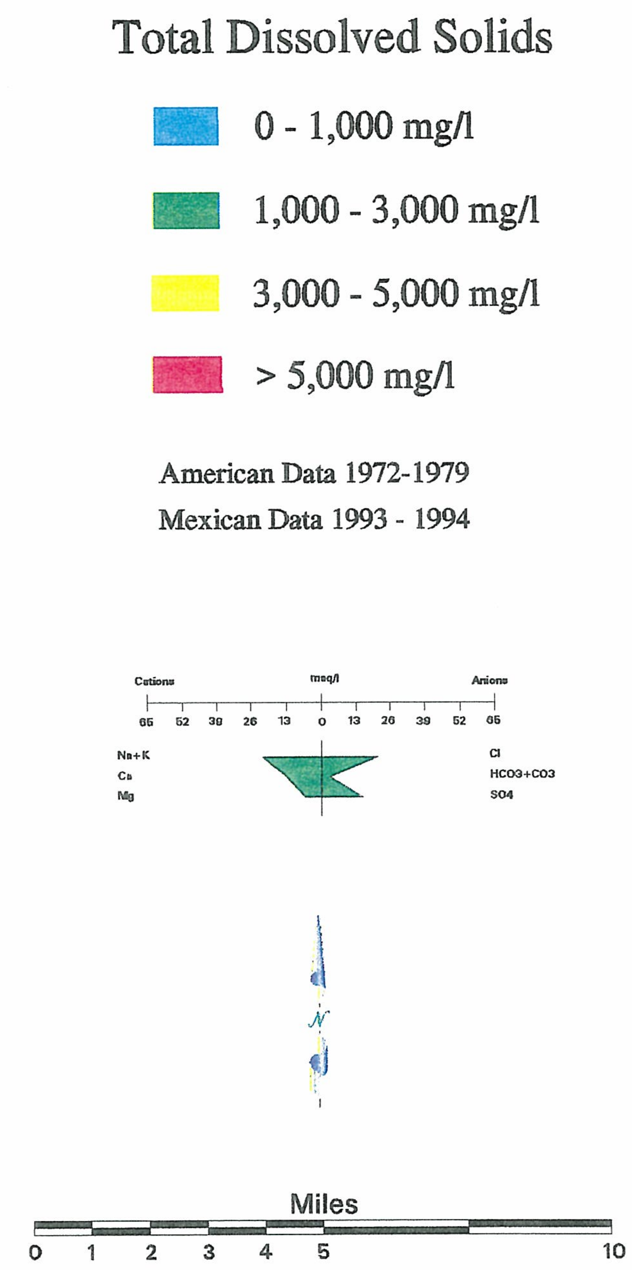
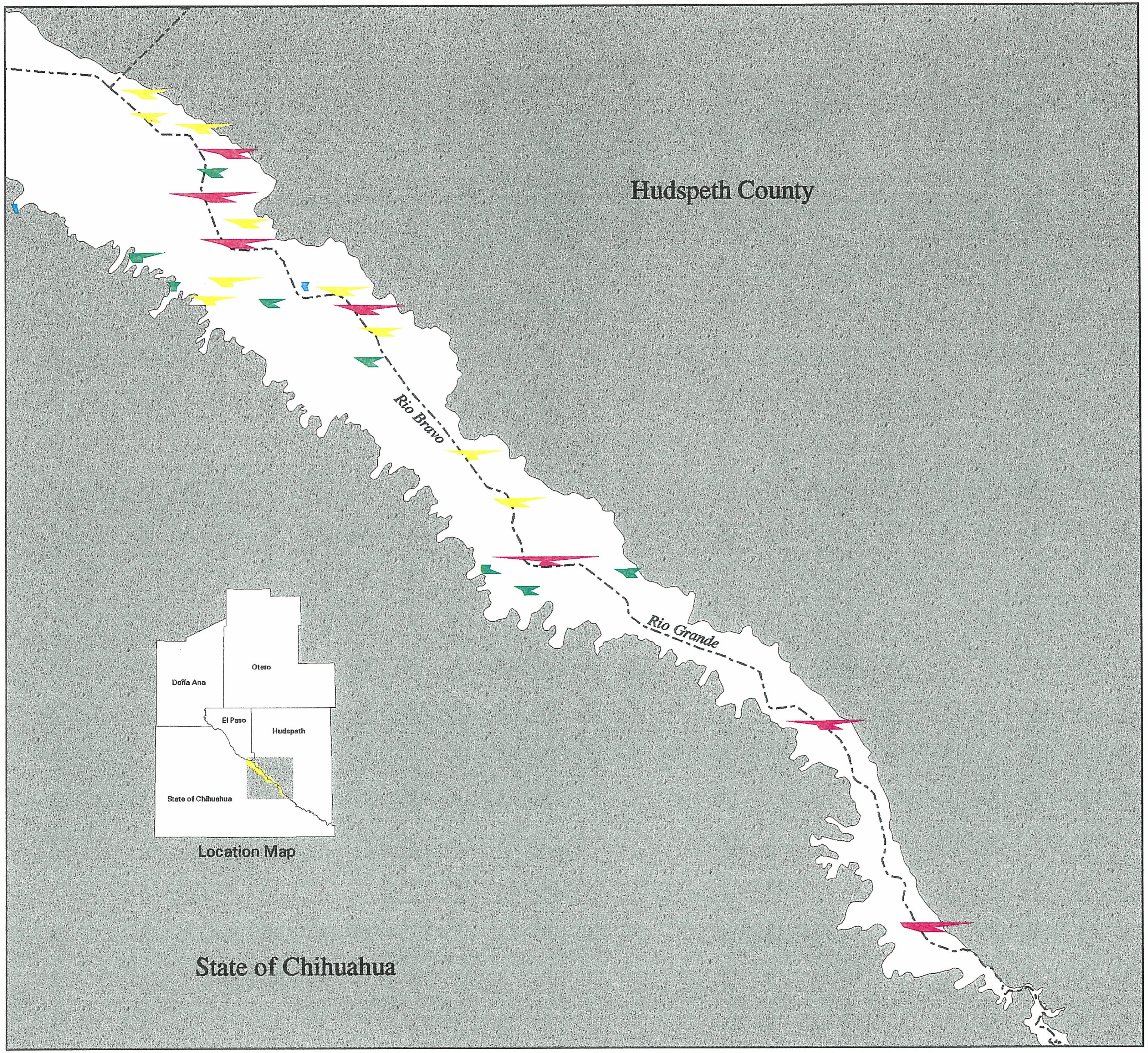


Figure 5.9. Stiff plots show Na-SO_4 ground waters with salinities usually less than 3,000 mg/L in the Rio Grande aquifer above the El Paso/Hudspeth County line (source of data, Texas Water Development Board; Comision Nacional del Agua).



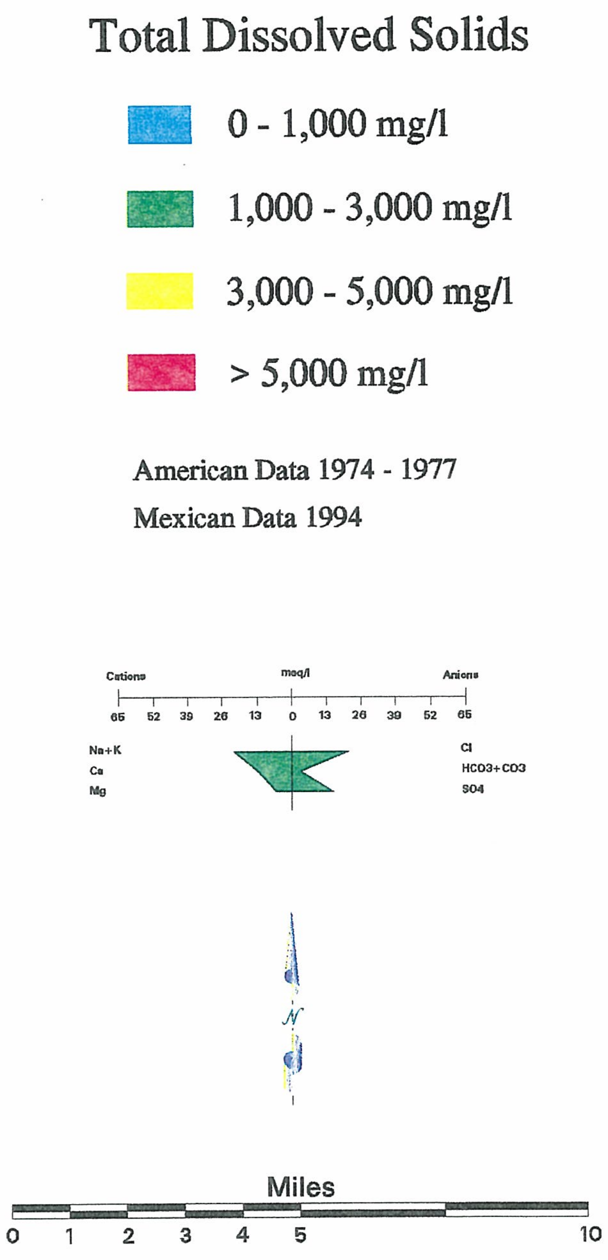


Figure 5.10. Stiff plots show Na-SO_4-Cl ground waters with salinities usually greater than 3,000 mg/L in the Rio Grande aquifer below the El Paso/Hudspeth County line (source of data, Texas Water Development Board; Comision Nacional del Agua).

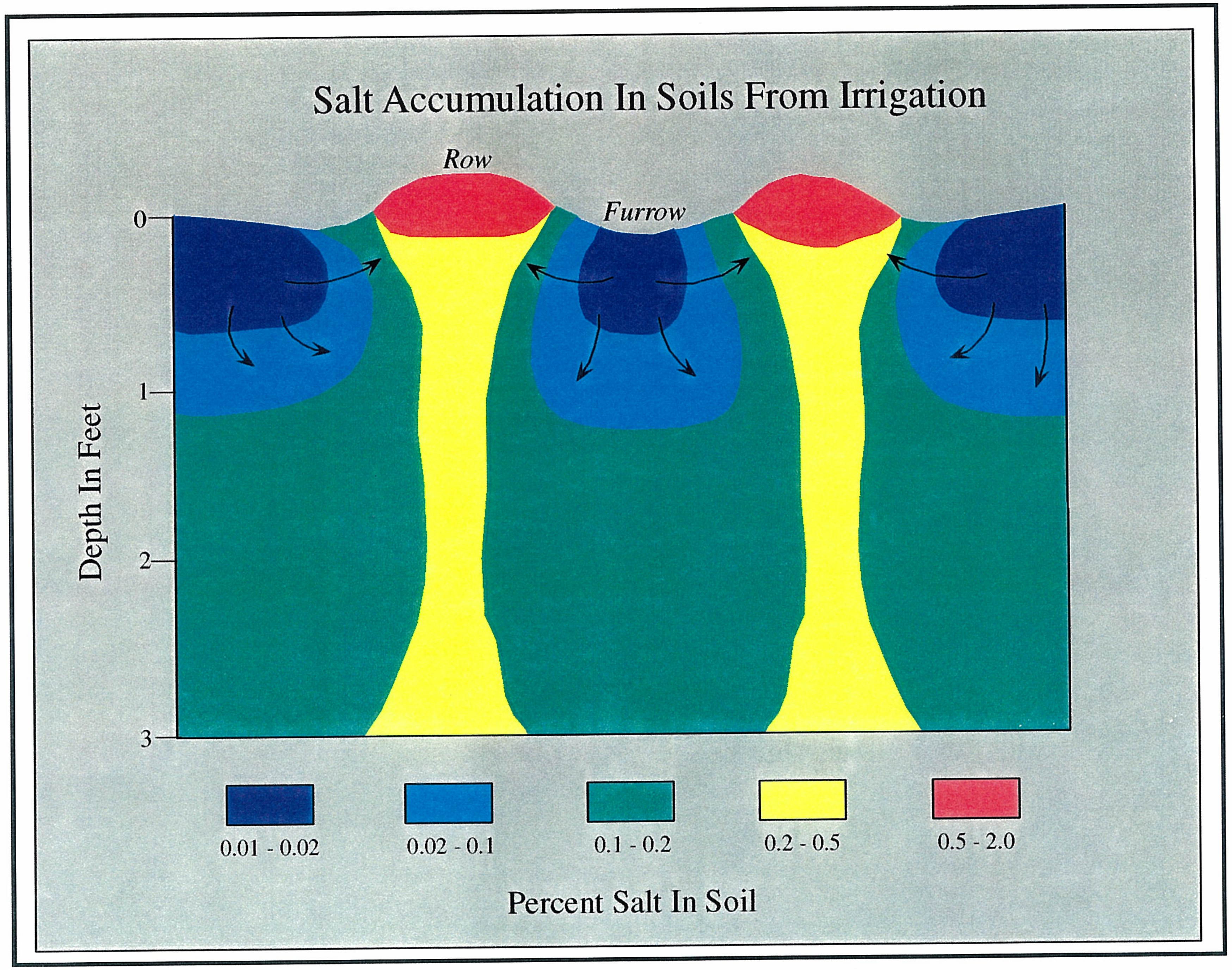


Figure 5.11. Diagram showing how dissolved salts in irrigation water become concentrated in irrigated soils due to high evapotranspiration rates (modified from Longnecker and Lyerly, 1959).

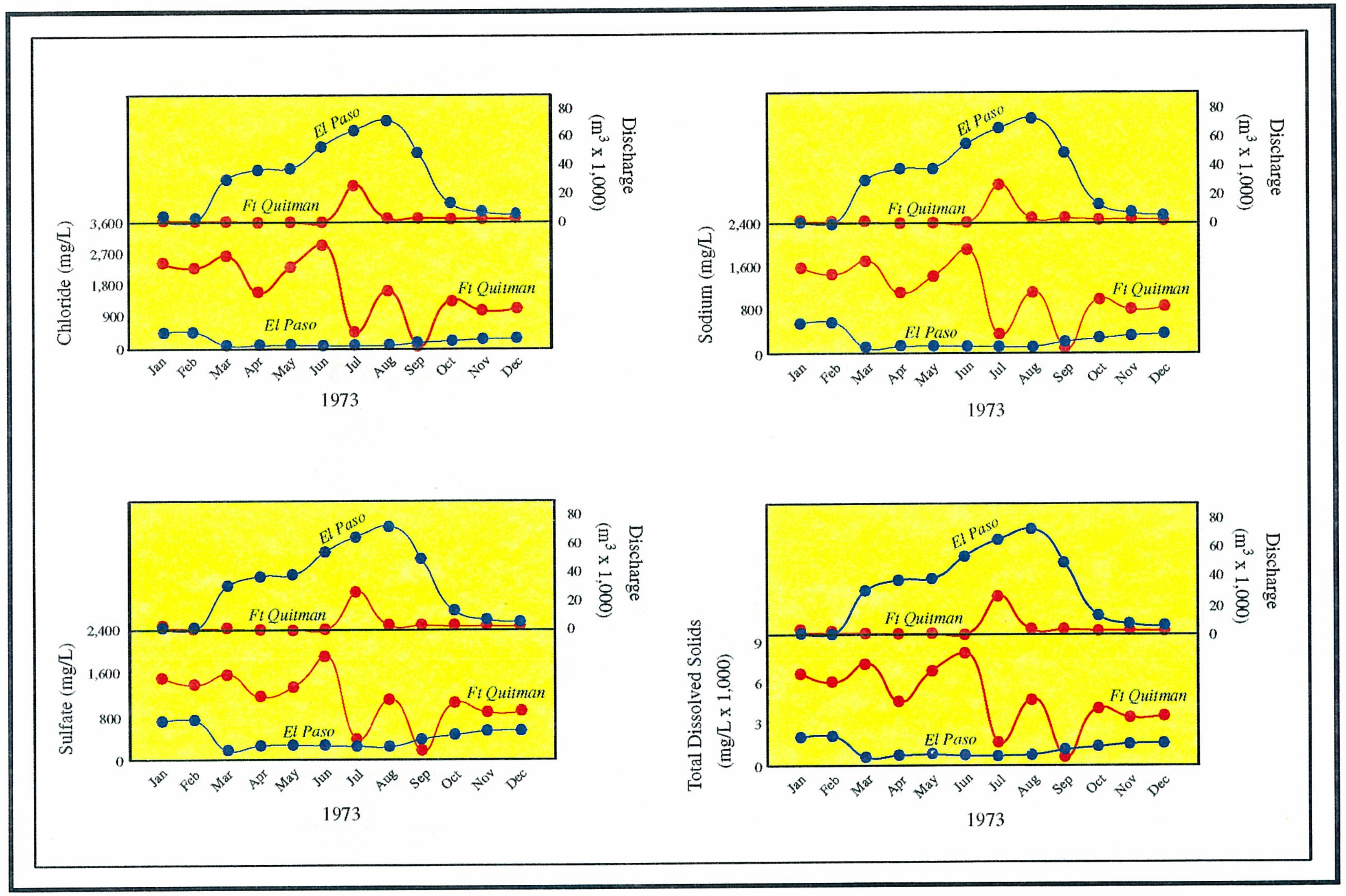


Figure 5.12a. Diagram comparing water quality and streamflow discharge for the Rio Grande at El Paso and Ft Quitman, 1973. Spatial changes in Cl, SO_4, Na, and TDS for most months indicate appreciable decline in surface-water quality downstream of El Paso. Water quality improves when discharge is high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

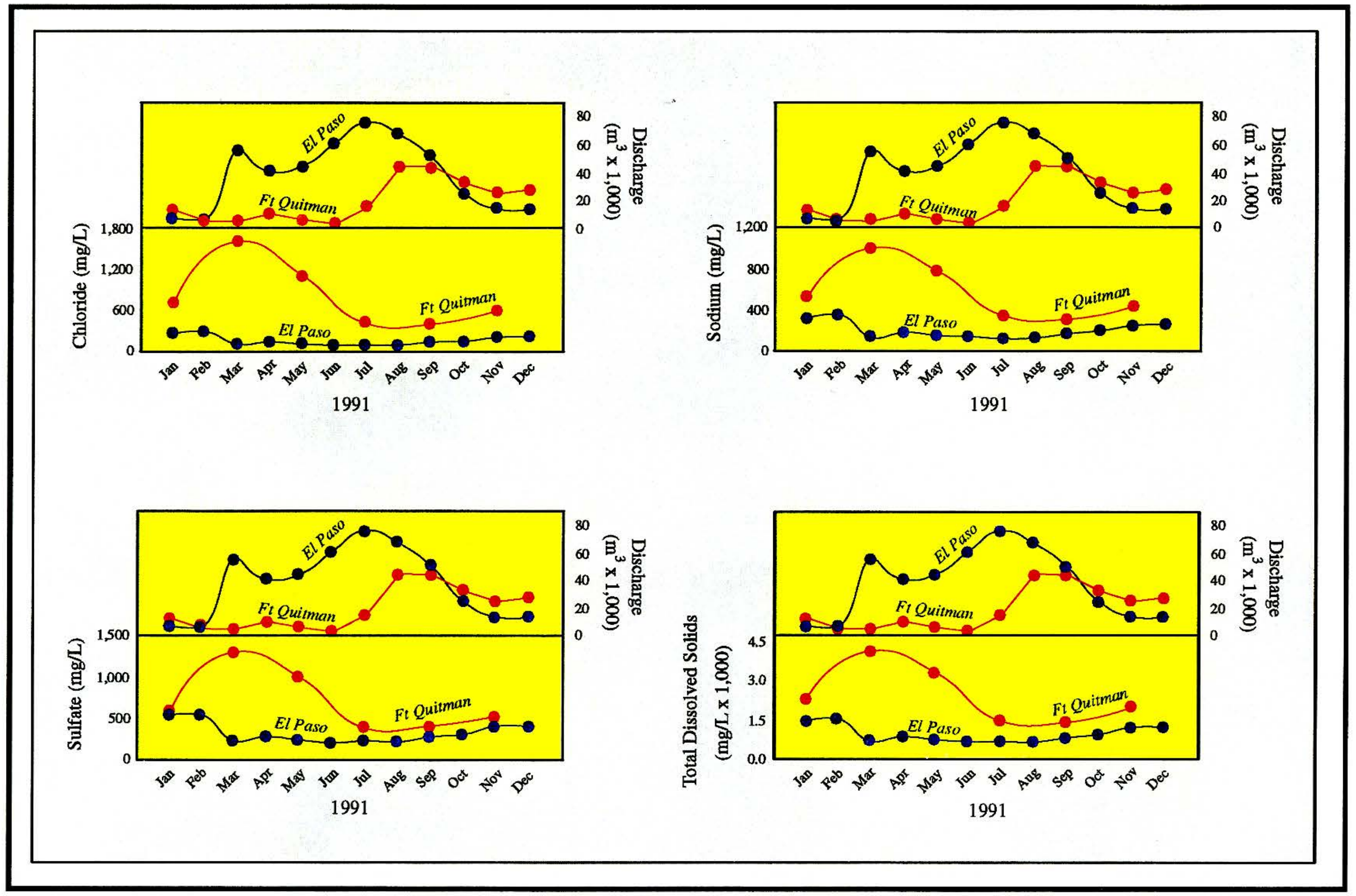


Figure 5.12b. Diagram comparing water quality and streamflow discharge for the Rio Grande at El Paso and Ft Quitman, 1991. Spatial changes in Cl, SO_4, Na, and TDS for most months indicate appreciable decline in surface-water quality downstream of El Paso. Water quality improves when discharge is high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

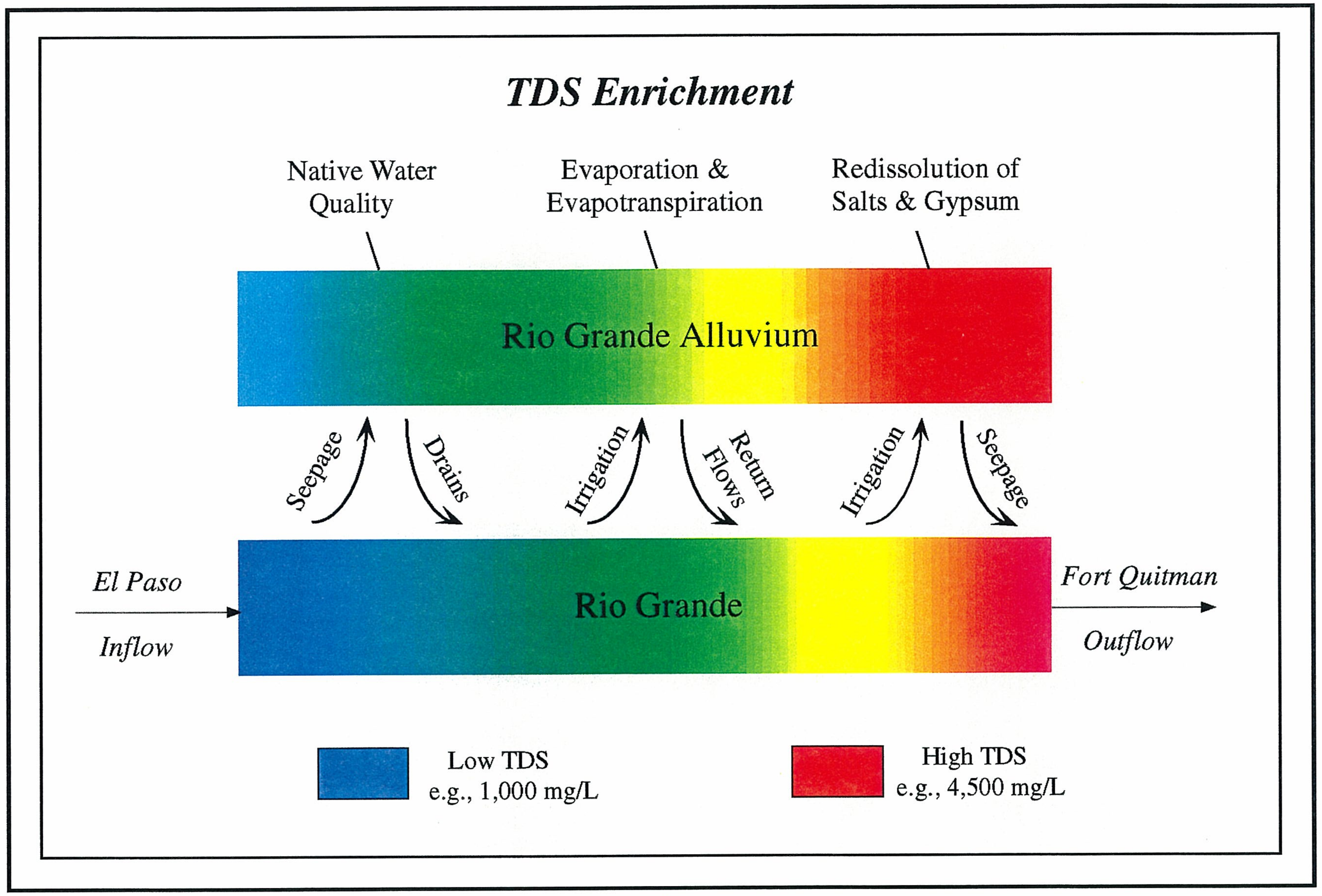
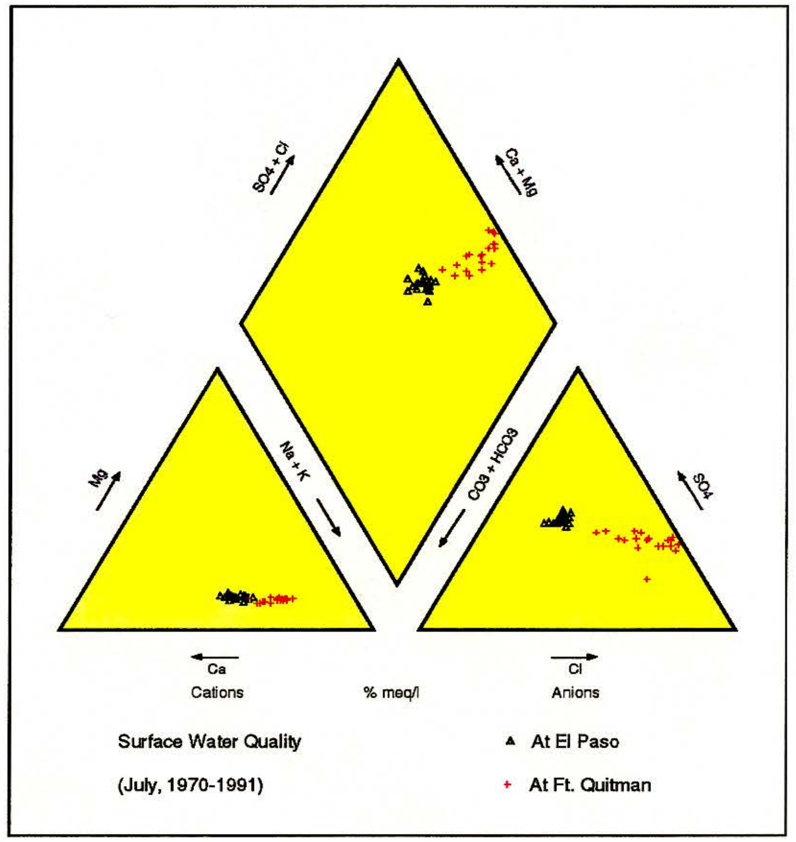
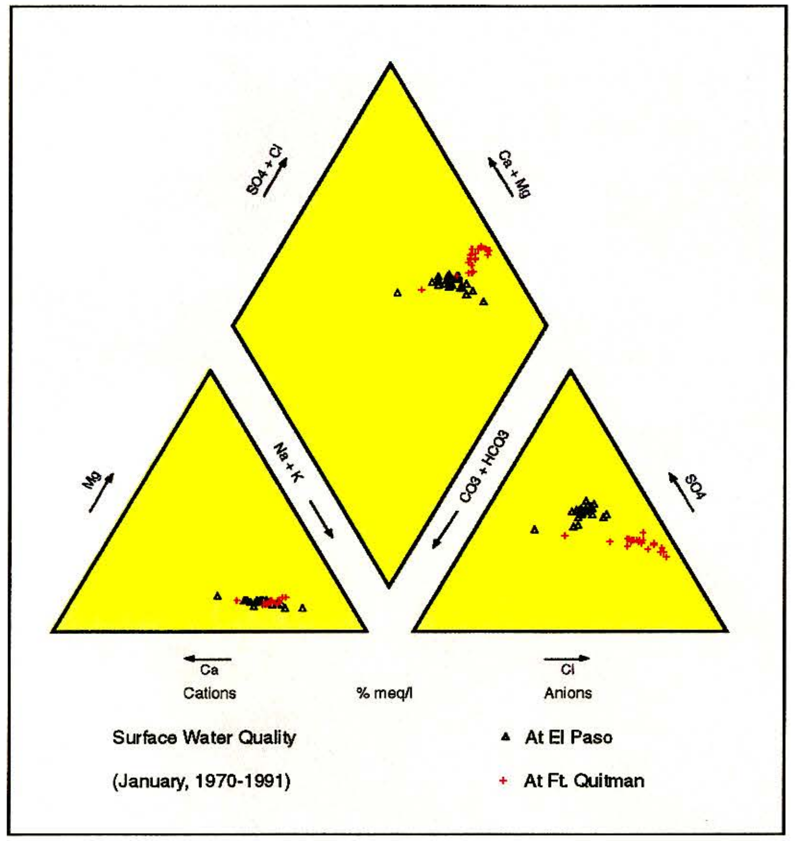


Figure 5.13. River salinities fluctuate downstream of El Paso due to inflows from several sources that both dilute and enrich Rio Grande water with respect to total dissolved solids. An overall pattern of salt water enrichment occurs between El Paso and Fort Quitman.





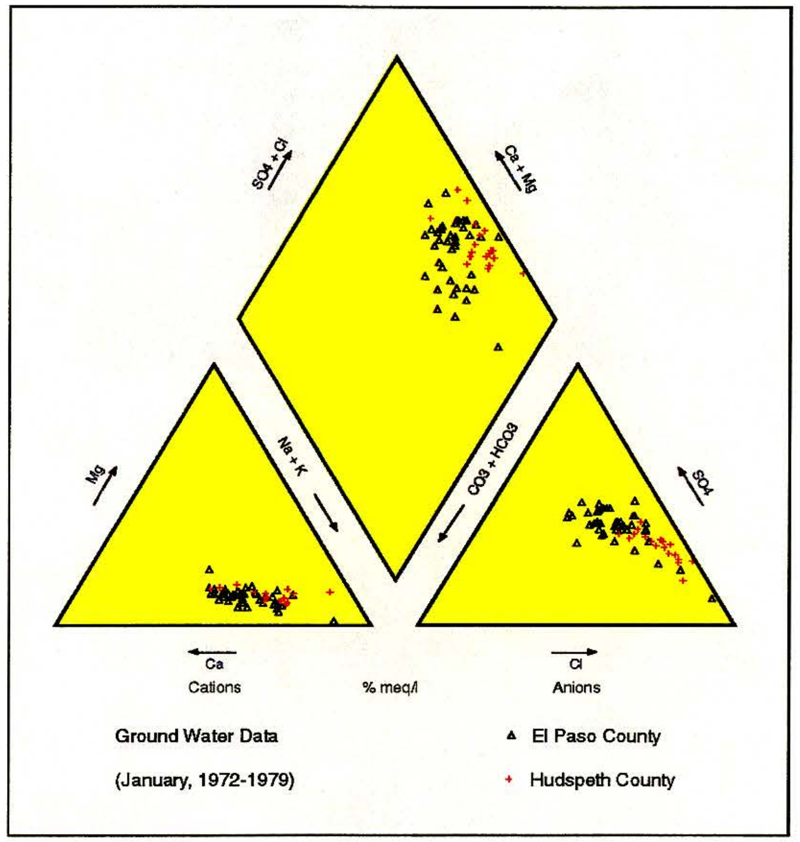


Figure 5.14a. Piper diagram shown in time series that illustrates surface water at the El Paso and Fort Quitman gage stations, January, 1970 - 1991. Surface water groups into distinct clusters of different hydrochemical types at the two gage stations (source of data, IBWC Water Bulletin series "Flow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

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

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

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

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

(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):

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

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

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O = Ca + Mg + 4HCO_3 \quad (5.5)$$

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:

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

or reversible ion exchange:

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

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:

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

(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-SO_4 water that is similar in composition to Rio Grande water, to a more concentrated Na-Cl-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.

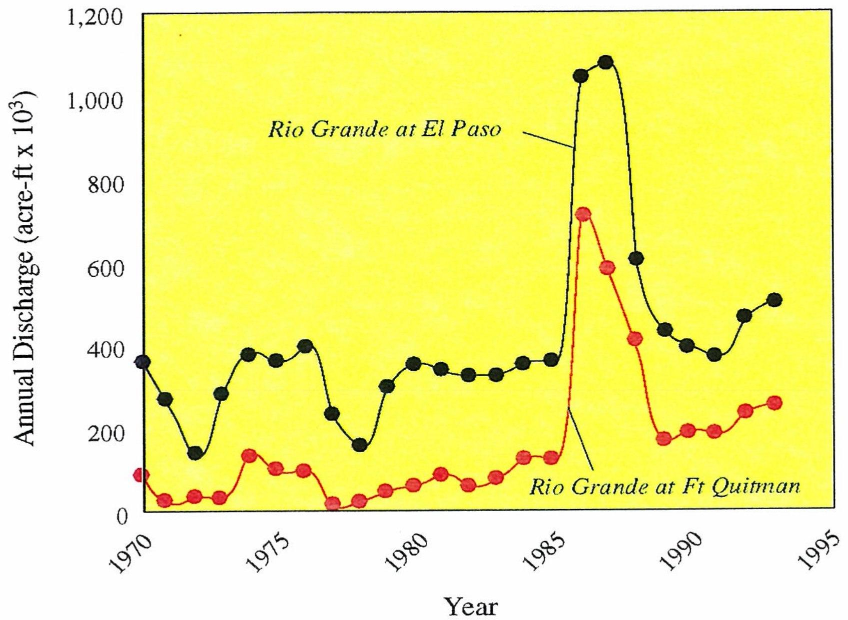


Figure 5.16. Comparison of discharge quantities in the Rio Grande at El Paso and Fort Quitman. Substantial loss of discharge is due to evapotranspiration by crops and other consumptive uses that tend to concentrate salts in fields and to enrich return flows with respect to total dissolved solids (source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

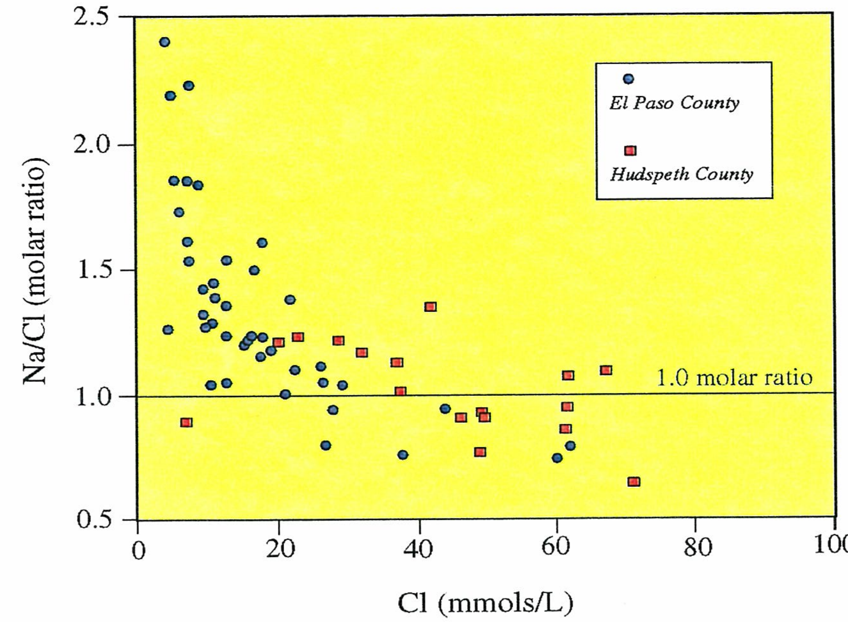


Figure 5.18. Scatter plot showing (Na/Cl) molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. (Na/Cl) molar ratios decrease from 2.4 to 0.6 with increasing chlorinity (source of data, Texas Water Development Board).

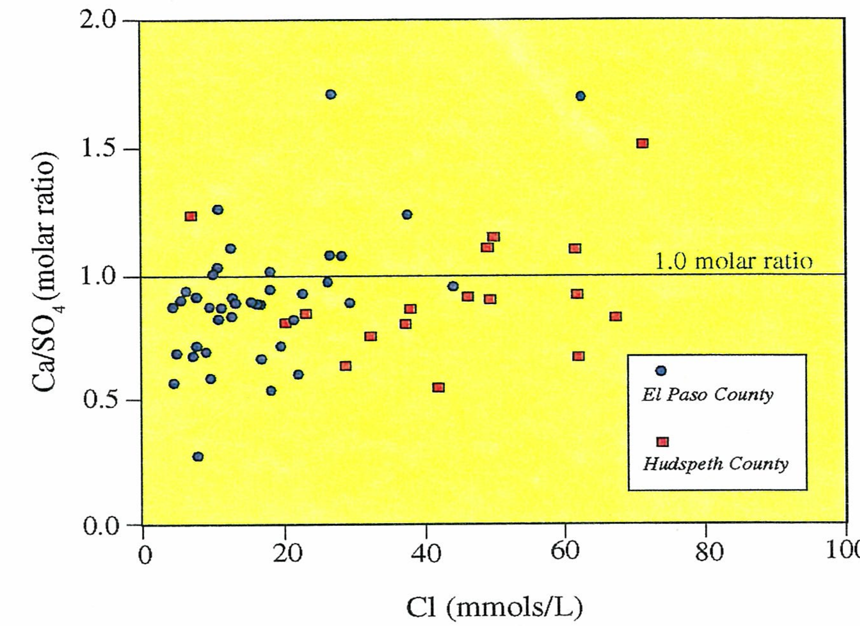


Figure 5.20. Scatter plot showing (Ca/SO_4) molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. Average (Ca/SO_4) ratios do not change with increasing chlorinity (source of data, Texas Water Development Board).

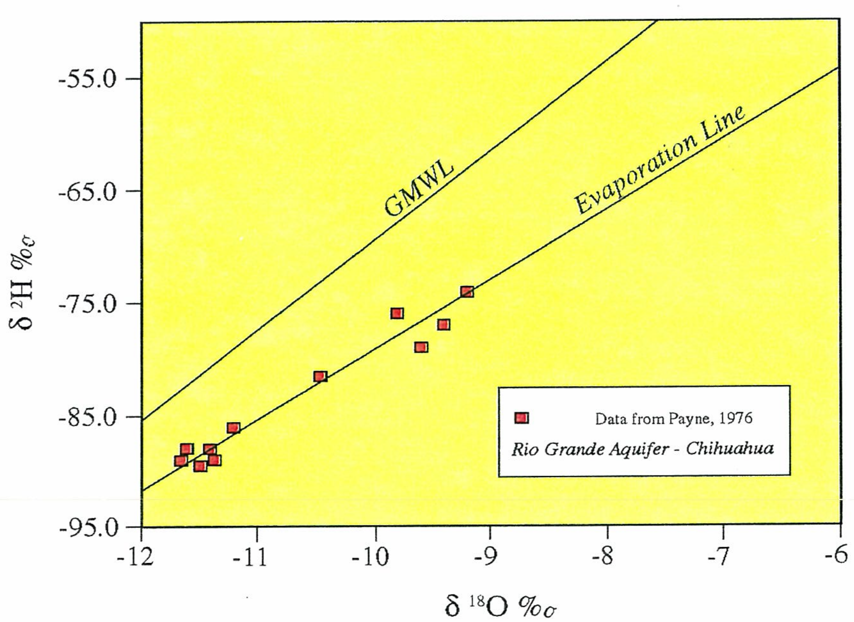


Figure 5.17. Binary plot of δ^2H versus $\delta^{18}O$ values for Rio Grande aquifer waters in the Mexican part of the alluvial aquifer. Stable hydrogen and oxygen isotope ratios in ground waters plot along the evaporation line, indicating evaporative enrichment of water, probably during irrigation (source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

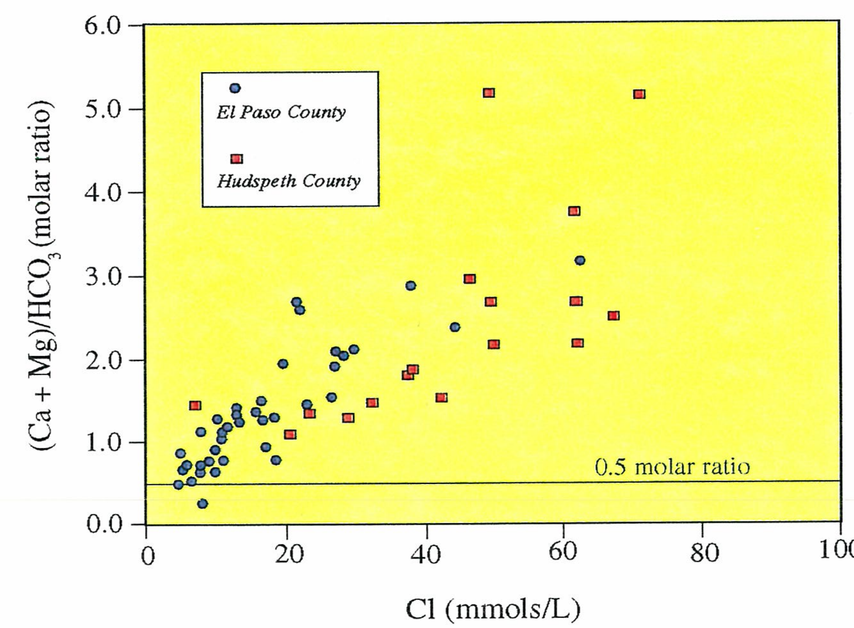


Figure 5.19. Scatter plot showing $(Ca+Mg)/HCO_3$ molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. Points above the 0.5 ratio line indicate a source of calcium and/or magnesium other than dissolution of carbonate rock (source of data, Texas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

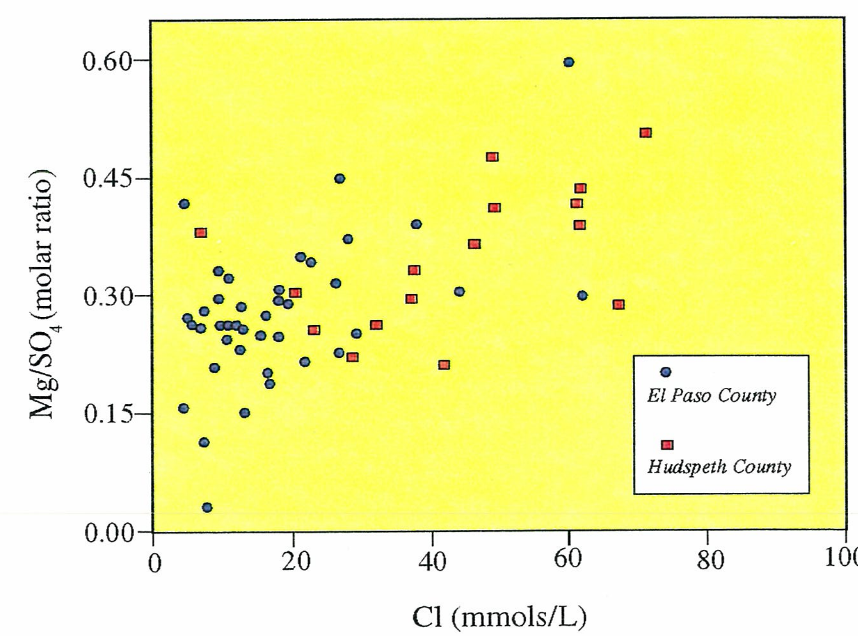


Figure 5.21. Scatter plot showing (Mg/SO_4) molar ratios vs molar Cl for samples collected from the Rio Grande aquifer in El Paso and Hudspeth Counties. Average (Mg/SO_4) ratios increase with increasing chlorinity, suggesting an additional source of Mg (source of data, Texas Water Development Board).

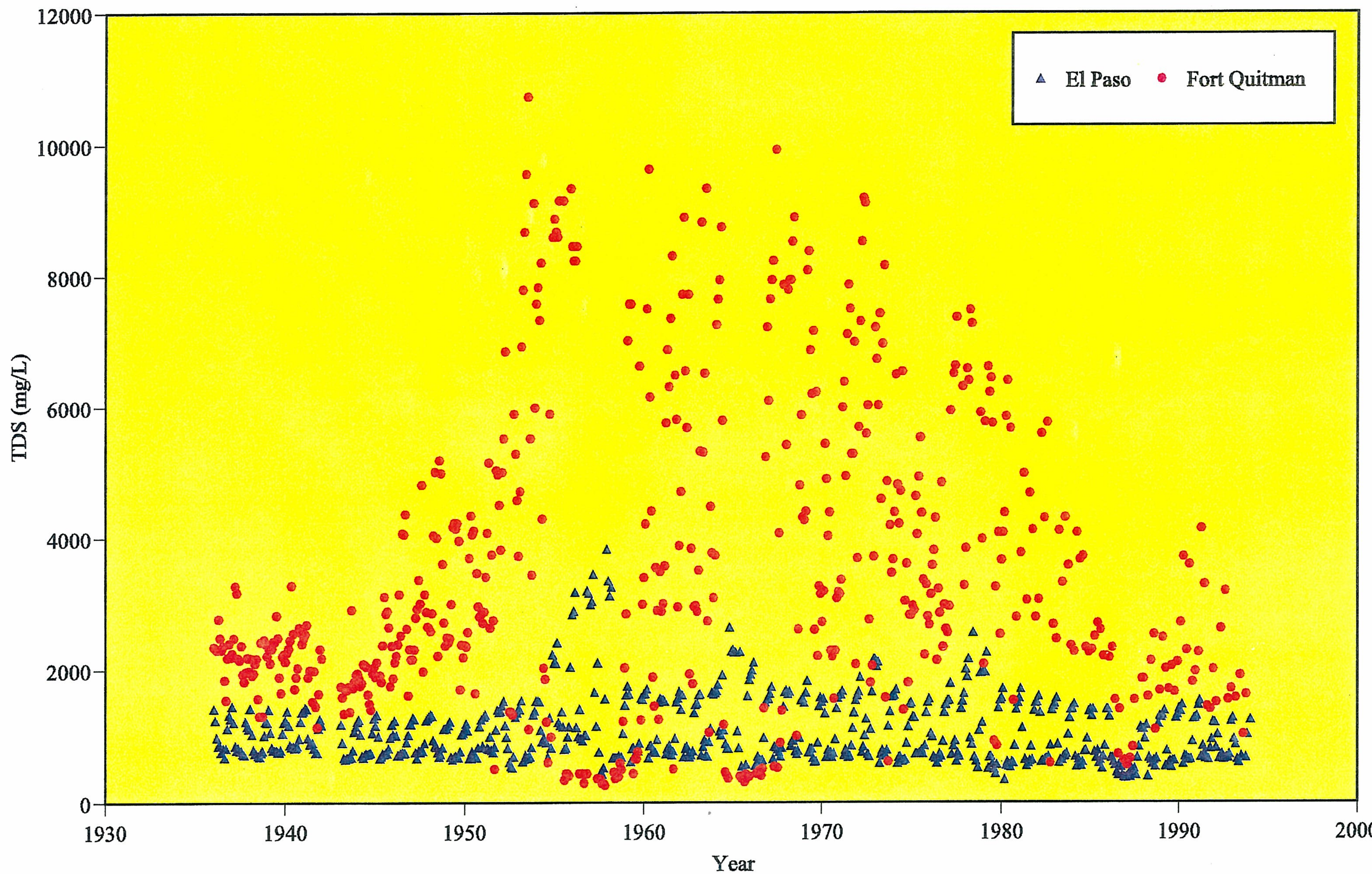


Figure 5.22. Time series graph of increasing salinities in the Rio Grande (source of data, IBWC Water Bulletin series "Flow of the Rio Grande and Related Data").

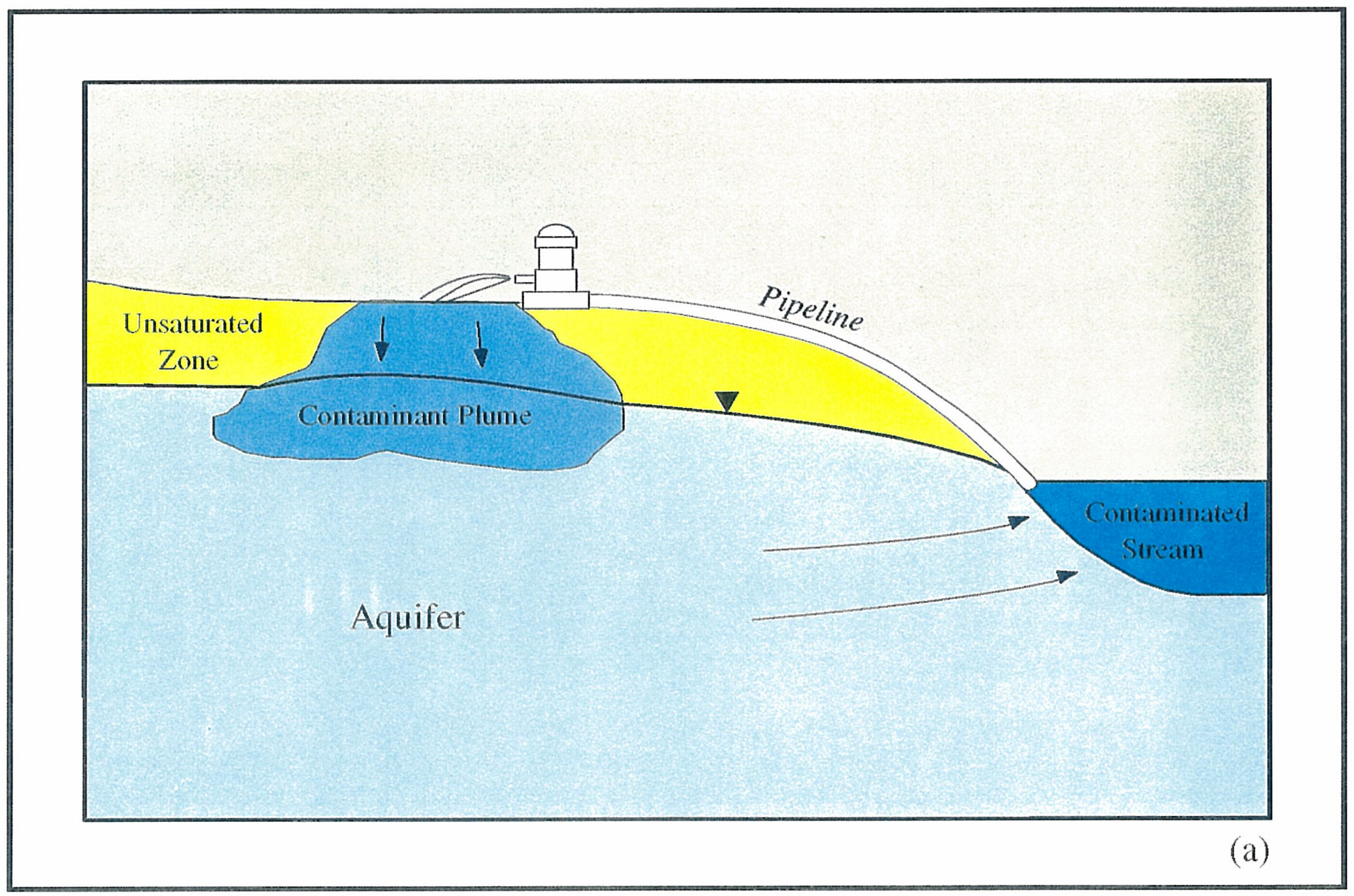


Figure 5.23a. Diagram illustrating contamination of an alluvial aquifer from a contaminated stream. Direct application of surface water may contaminate the aquifer.

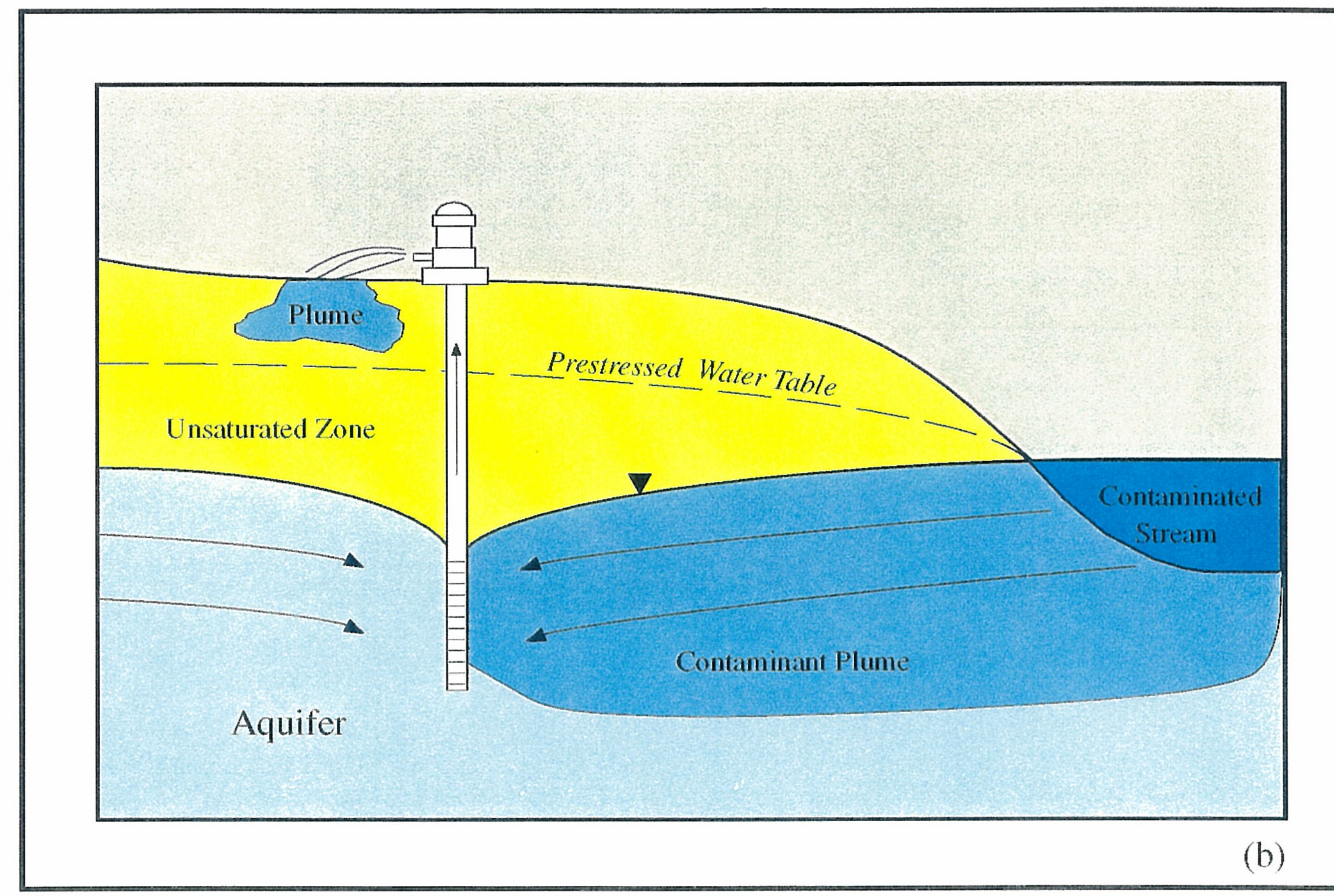
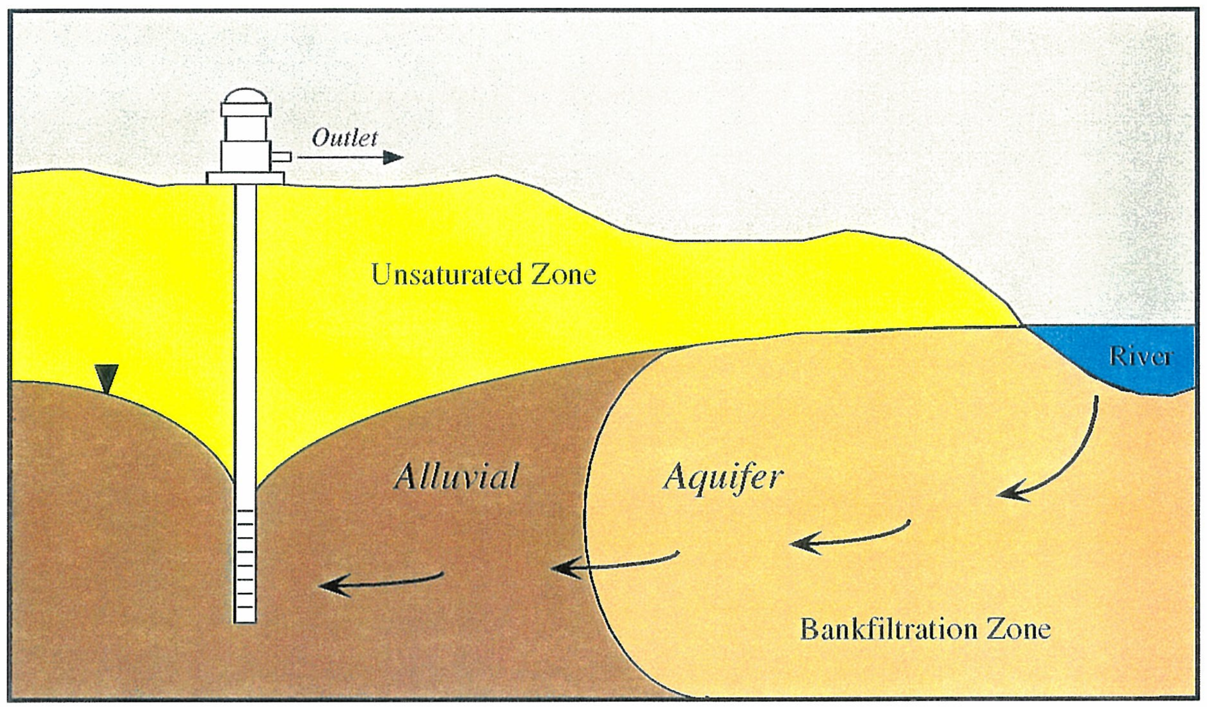
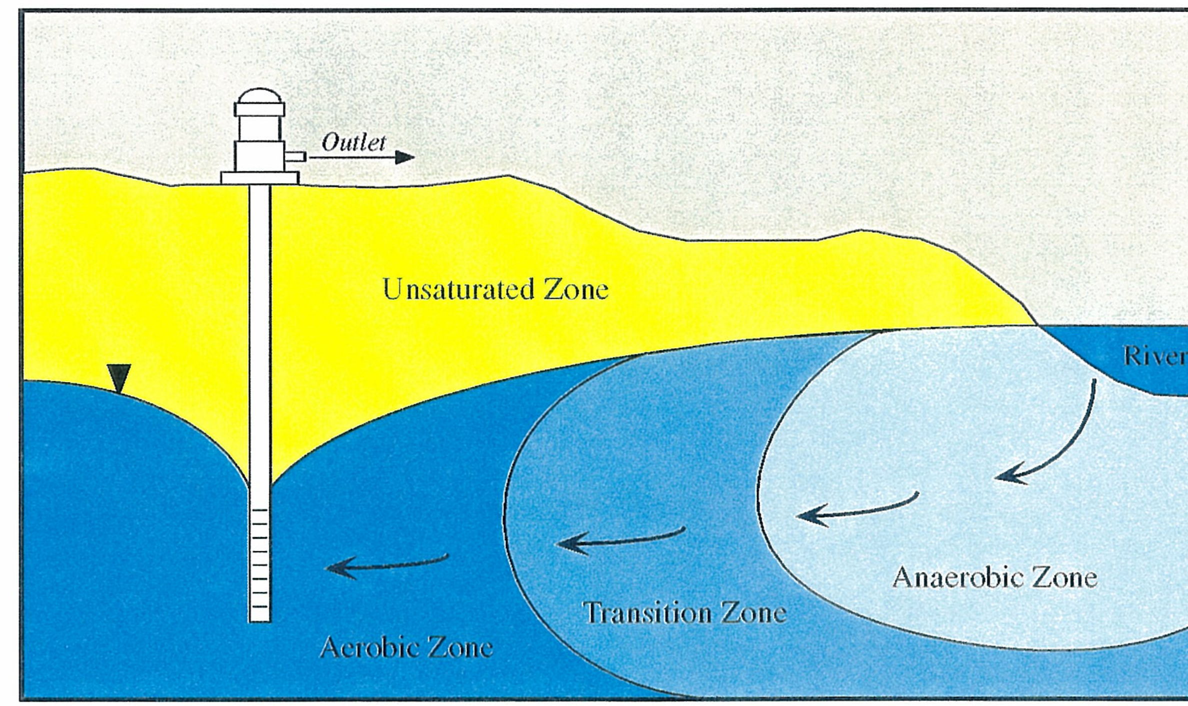


Figure 5.23b. Diagram illustrating contamination of an alluvial aquifer from a contaminated stream. Induced infiltration of contaminated surface water may contaminate the aquifer.



(a)

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.



(b)

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 ft^2/day to 9,300 ft^2/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 mi^2) 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 mi^2 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.

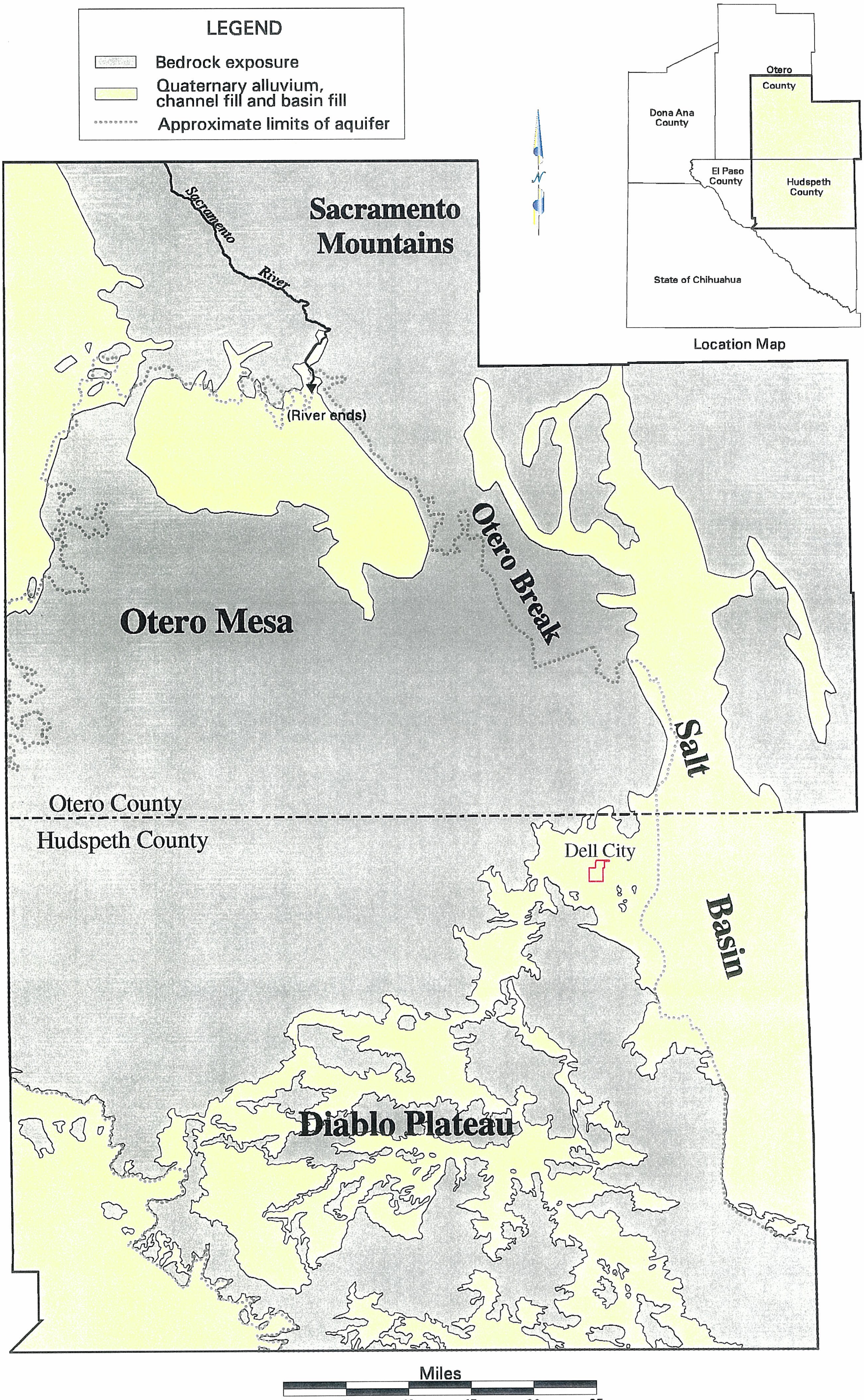


Figure 6.1. Location and extent of the Diablo Plateau aquifer and surrounding region.

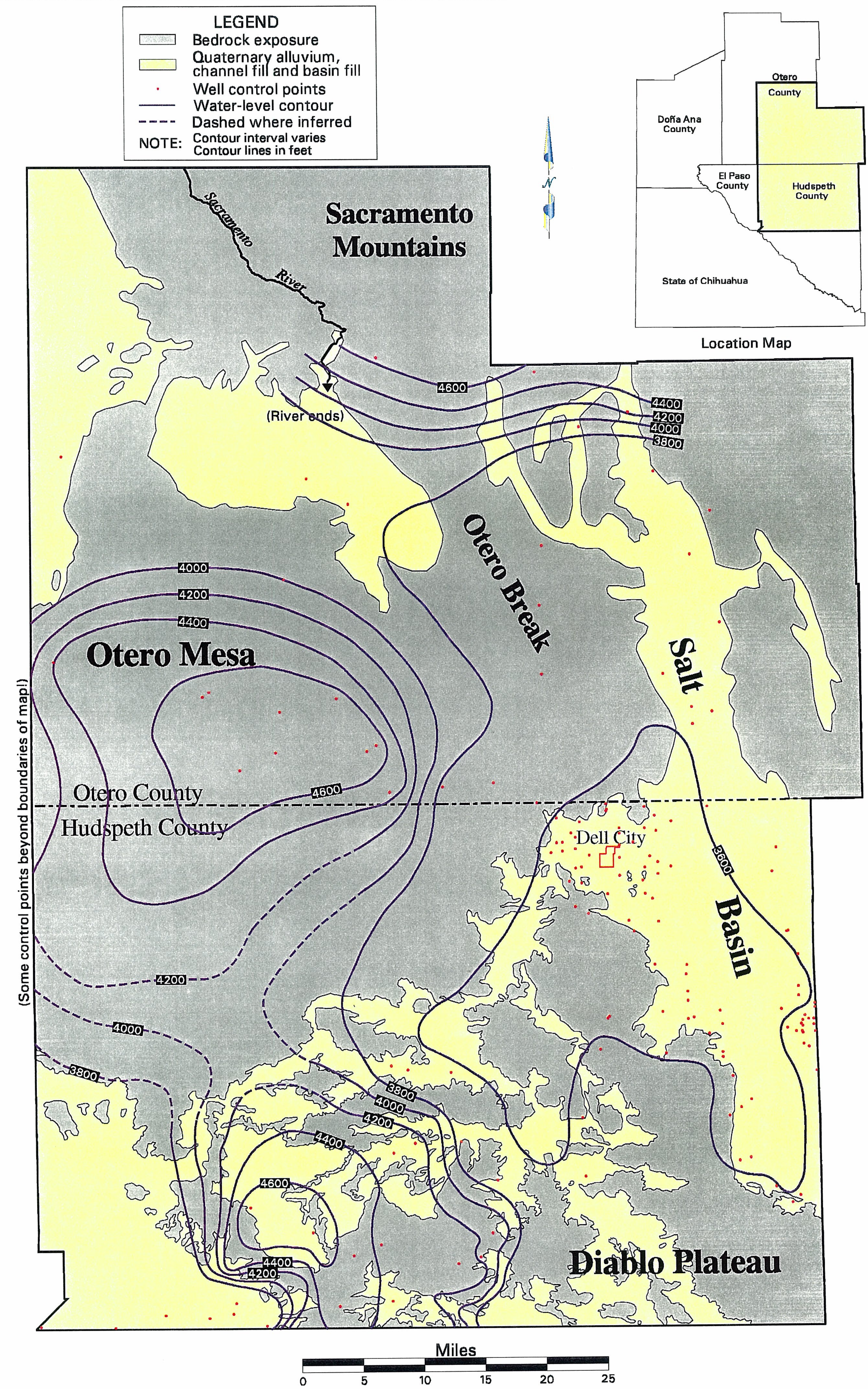


Figure 6.2. Regional potentiometric surface map for the Diablo Plateau aquifer and surrounding regions. Data for the Dell City area gathered in 1994. Other data in less developed and undeveloped areas gathered at various times. We assume quasi-steady state ground-water flow in undeveloped areas (source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

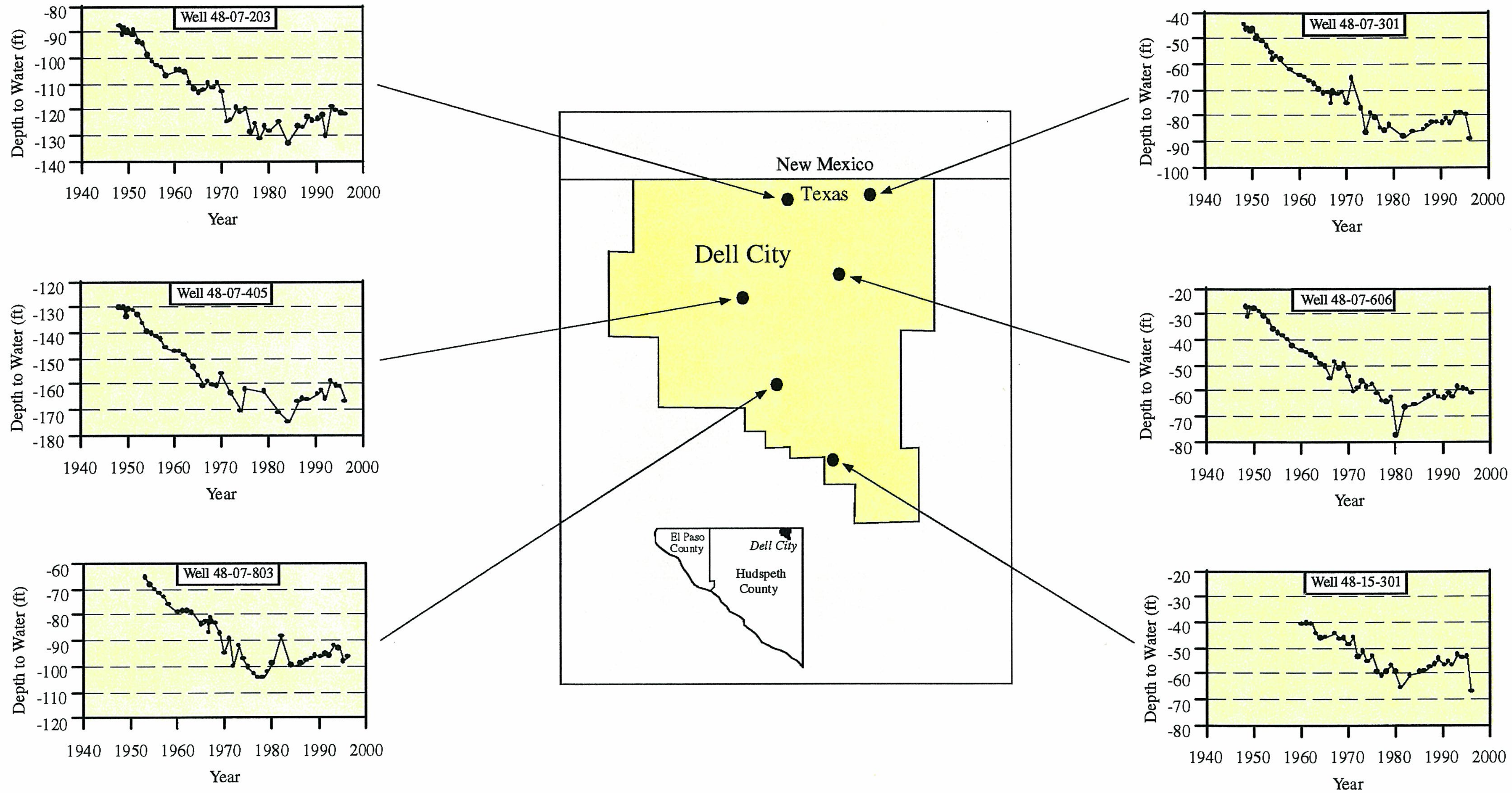


Figure 6.3. Hydrographs of selected wells in the Dell City area (modified from Ashworth, 1995).

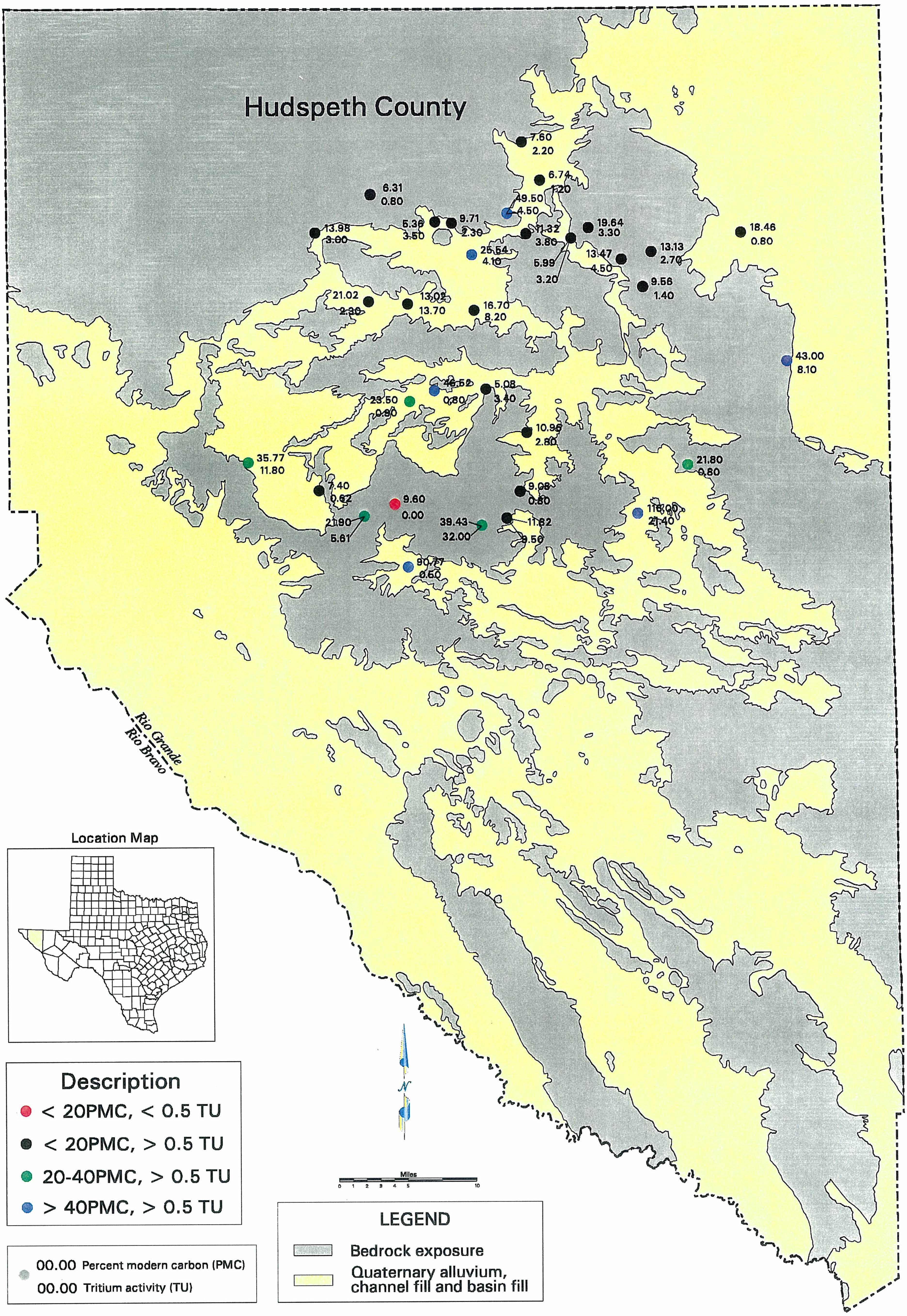


Figure 6.4. Map showing tritium activities (TU) and percent modern carbon (PMC) of ground water in the Texas portion of the Diablo Plateau aquifer (source of data, Kreitler and others, 1986).

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:

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

Dolomite dissolution:

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

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

Gypsum dissolution:

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

Halite dissolution:

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

and ion exchange:

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

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

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 $\delta^{18}O$) 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

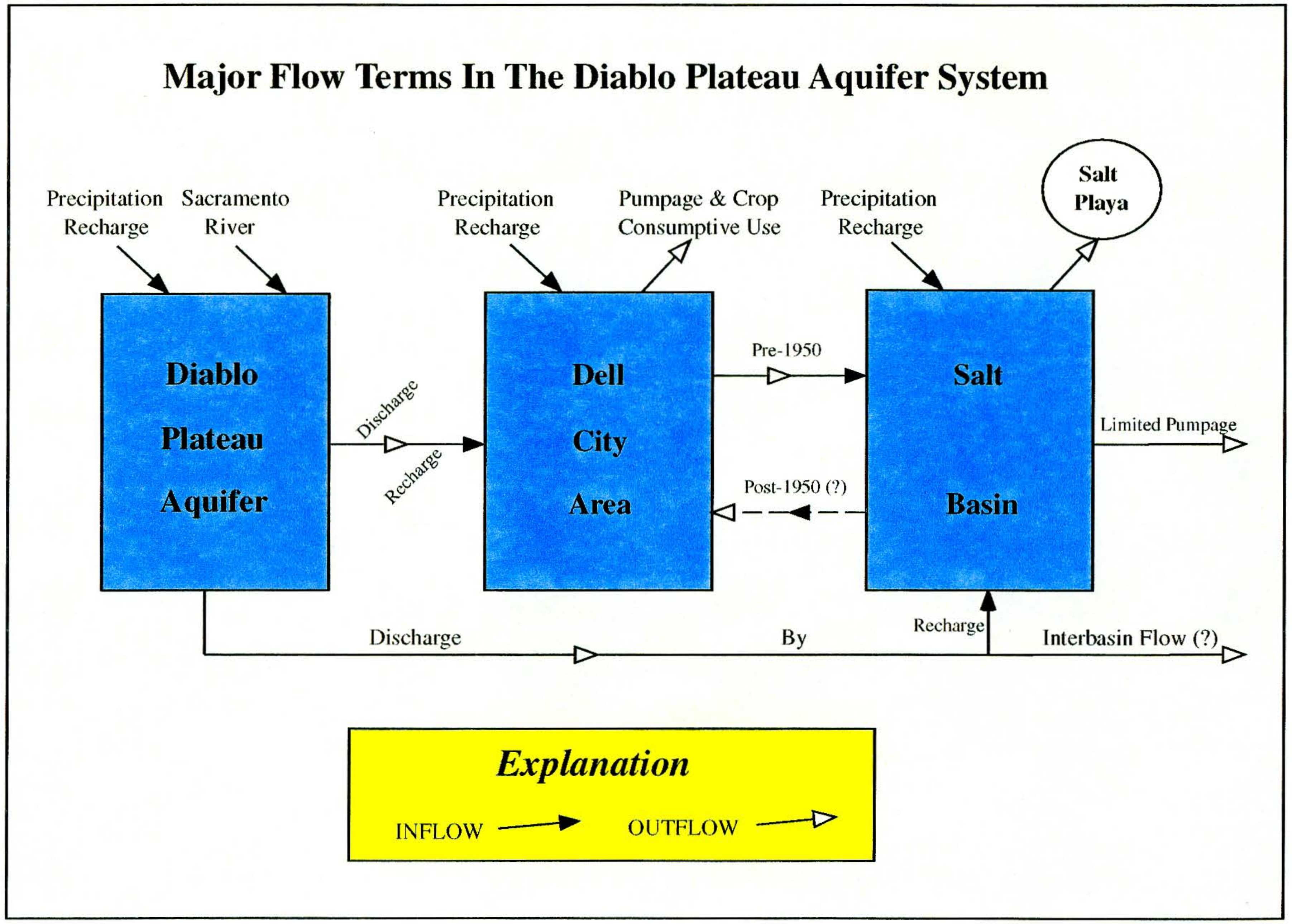


Figure 6.5. Major flow terms in the Diablo Plateau aquifer system.

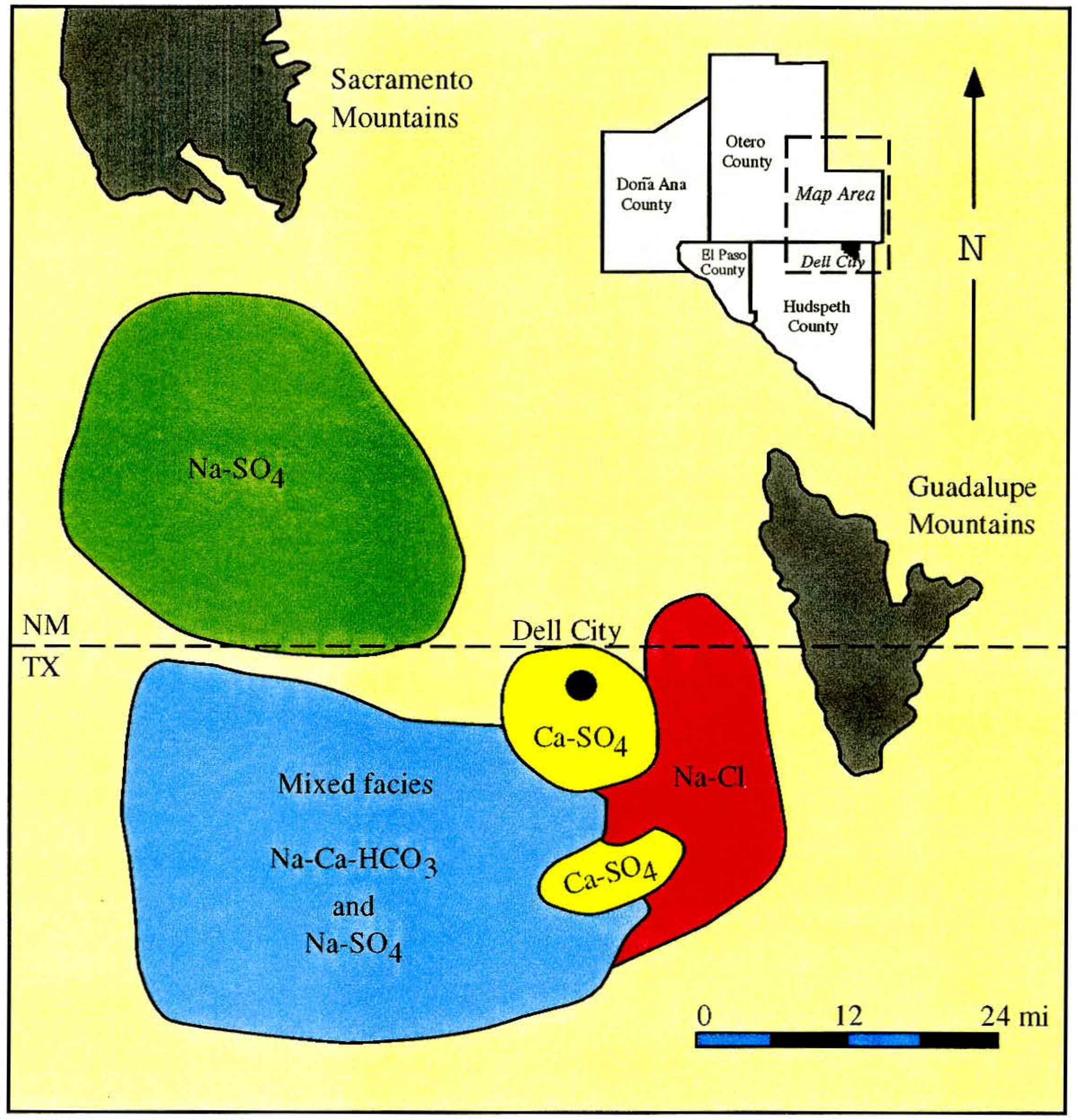


Figure 6.6. Areal distribution of ground-water facies in parts of the Texas and New Mexico portions of the Diablo Plateau aquifer (source of data, Texas Water Development Board; Kreitler and others, 1986; Mayer, 1995).

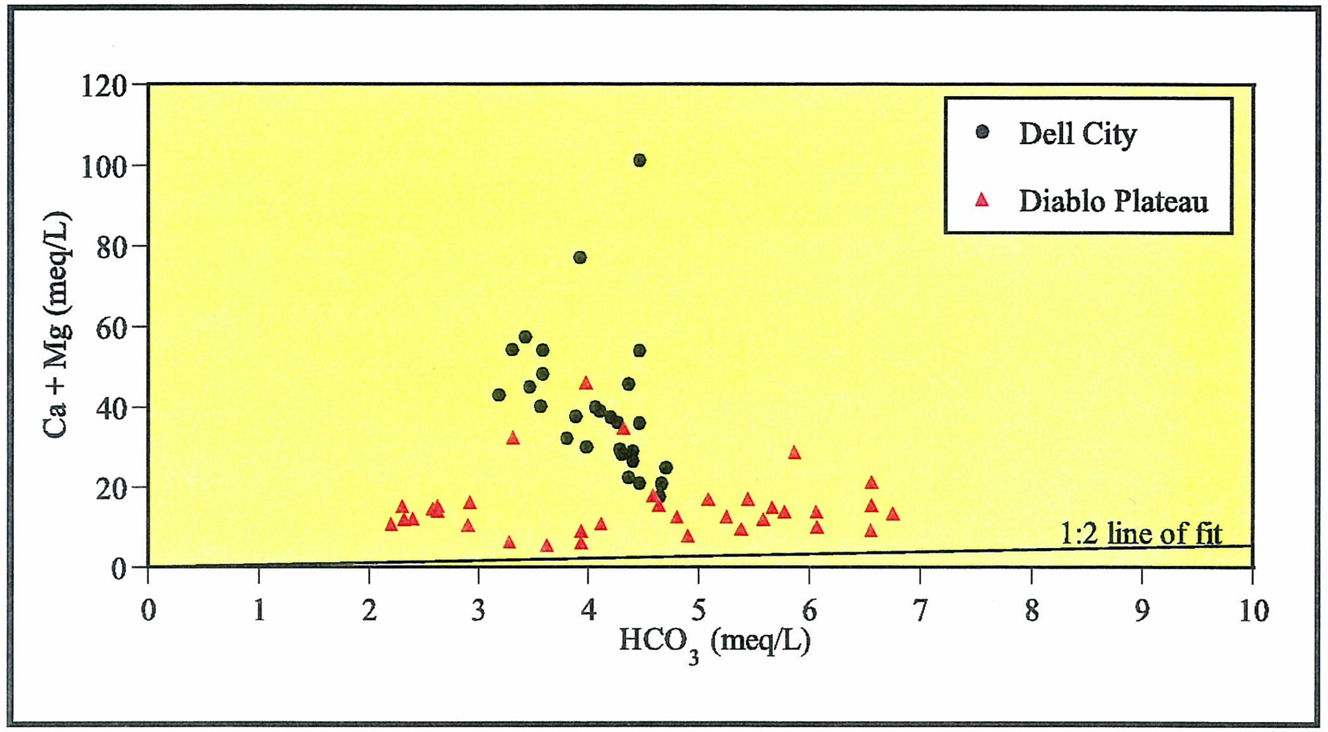


Figure 6.7. Plot of (Ca + Mg) vs HCO_3 .

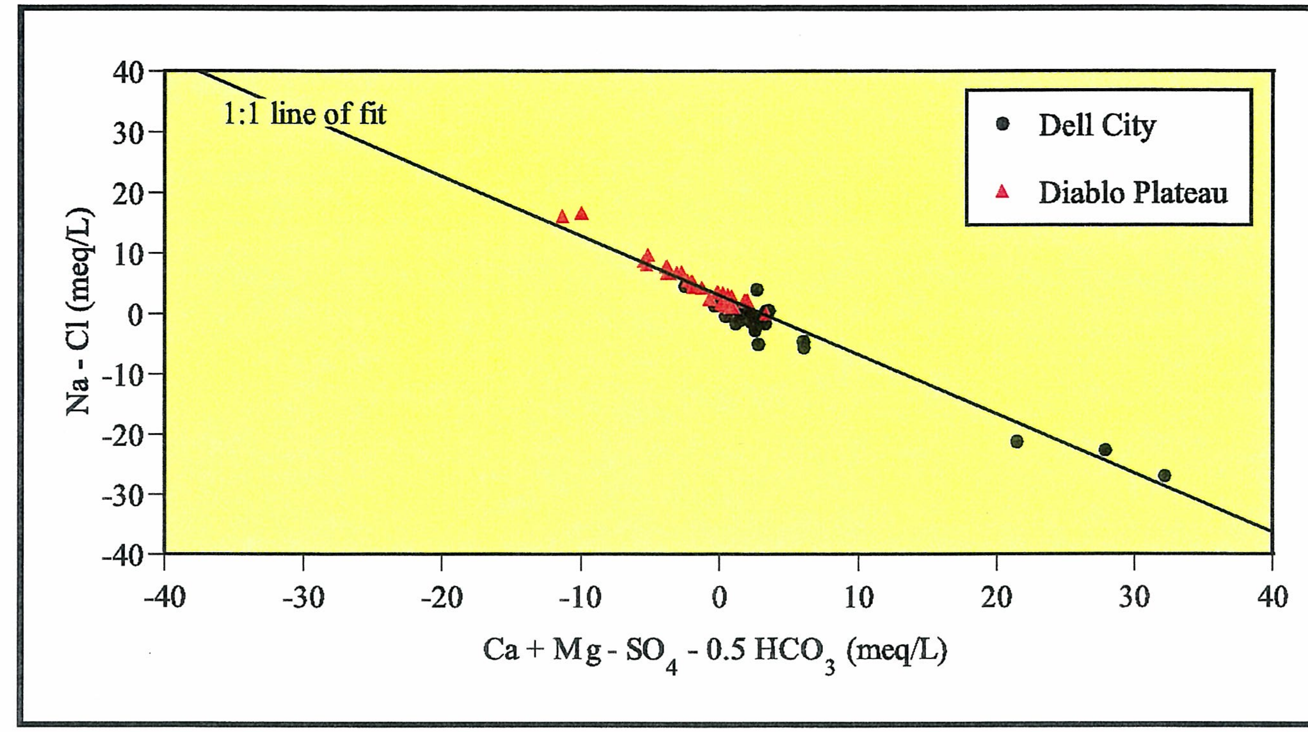


Figure 6.9. Plot of (Na - Cl) vs (Ca + Mg - SO_4 - 0.5HCO_3).

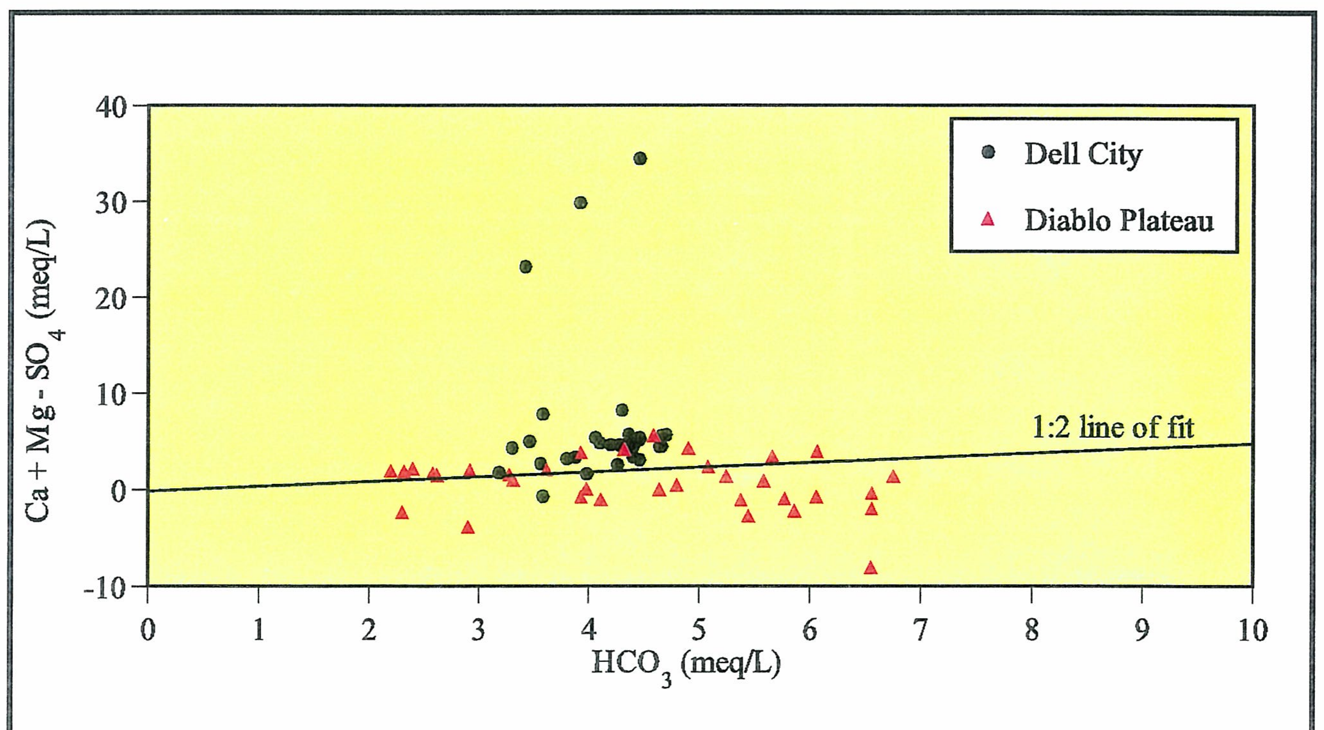


Figure 6.8. Plot of (Ca + Mg - SO_4) vs HCO_3.

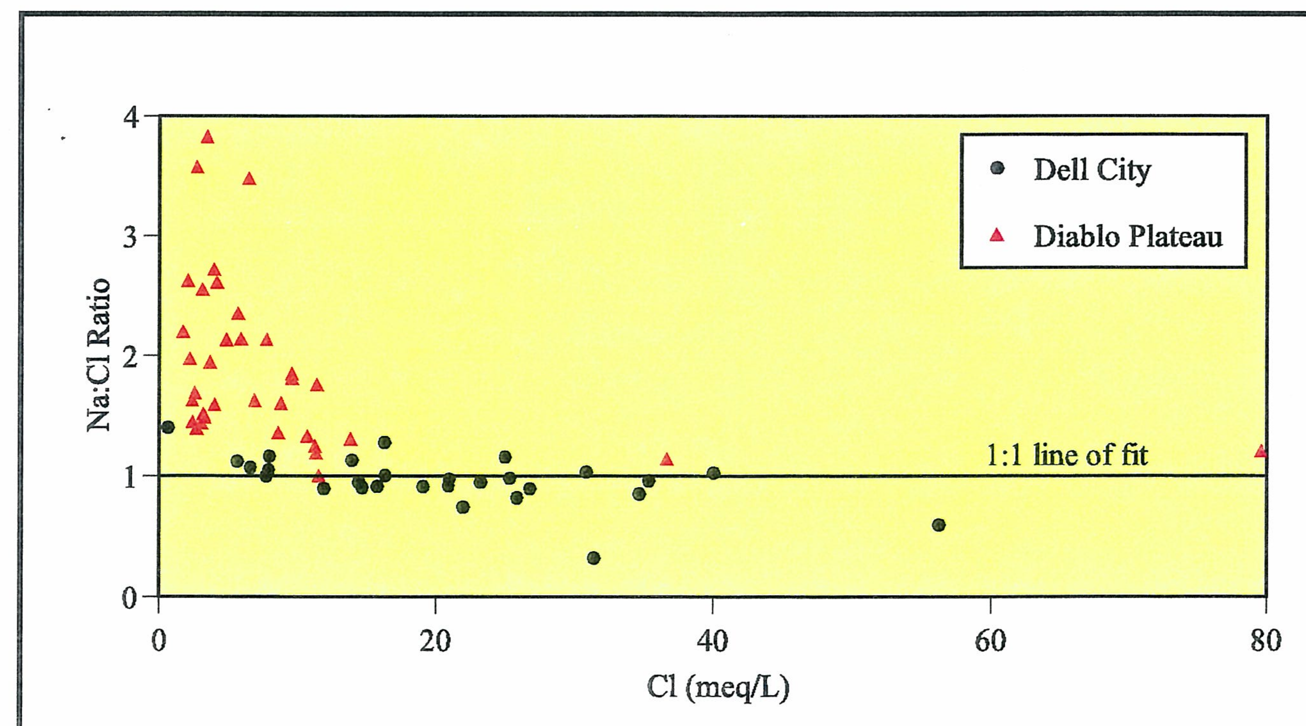


Figure 6.10. Plot of (Na/Cl) ratio vs Cl.

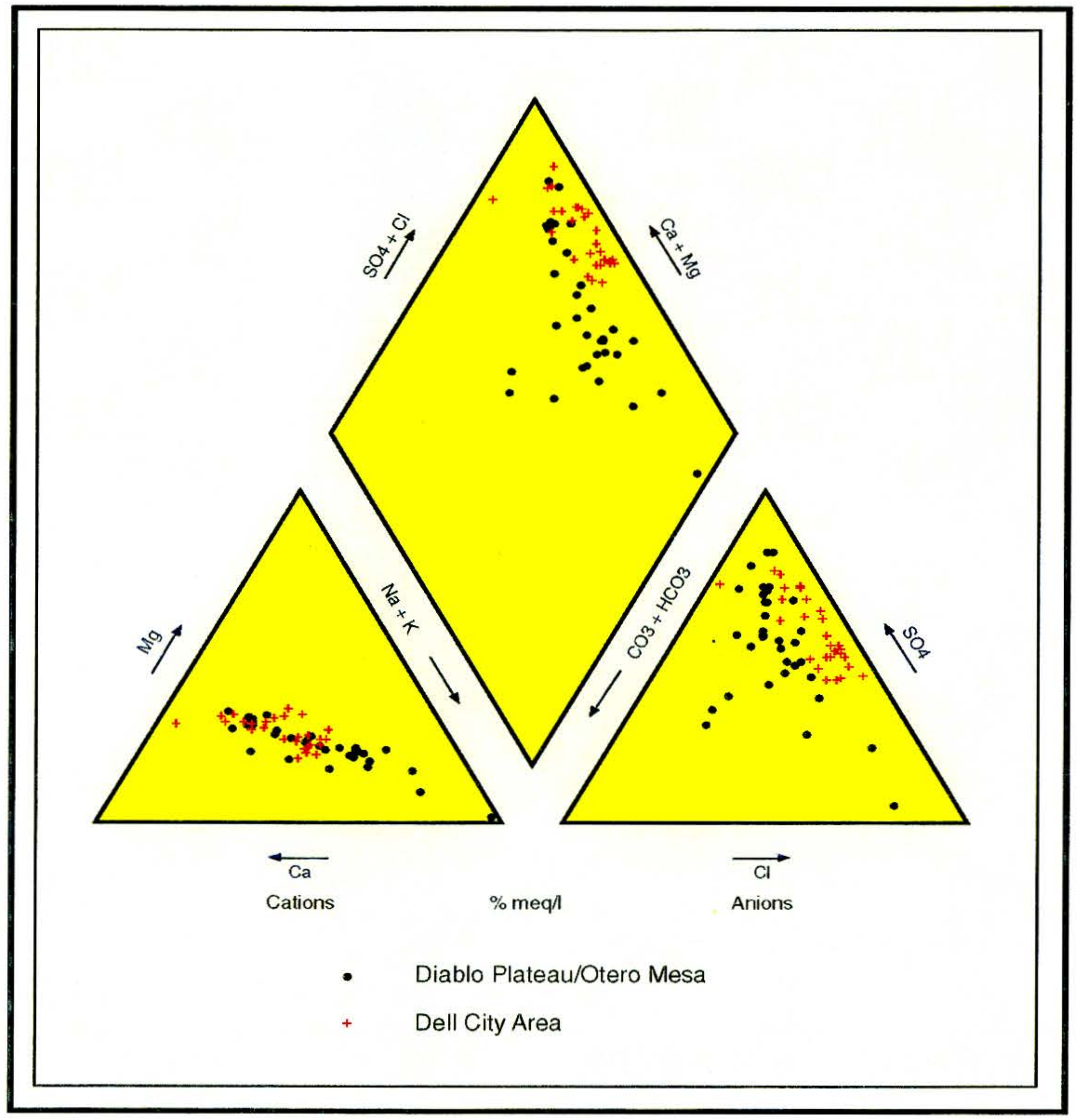


Figure 6.11. Piper diagram illustrating geochemical types for ground water in the Diablo Plateau aquifer (source of data, Texas Water Development Board; Kreitler and others, 1986; Mayer, 1995).

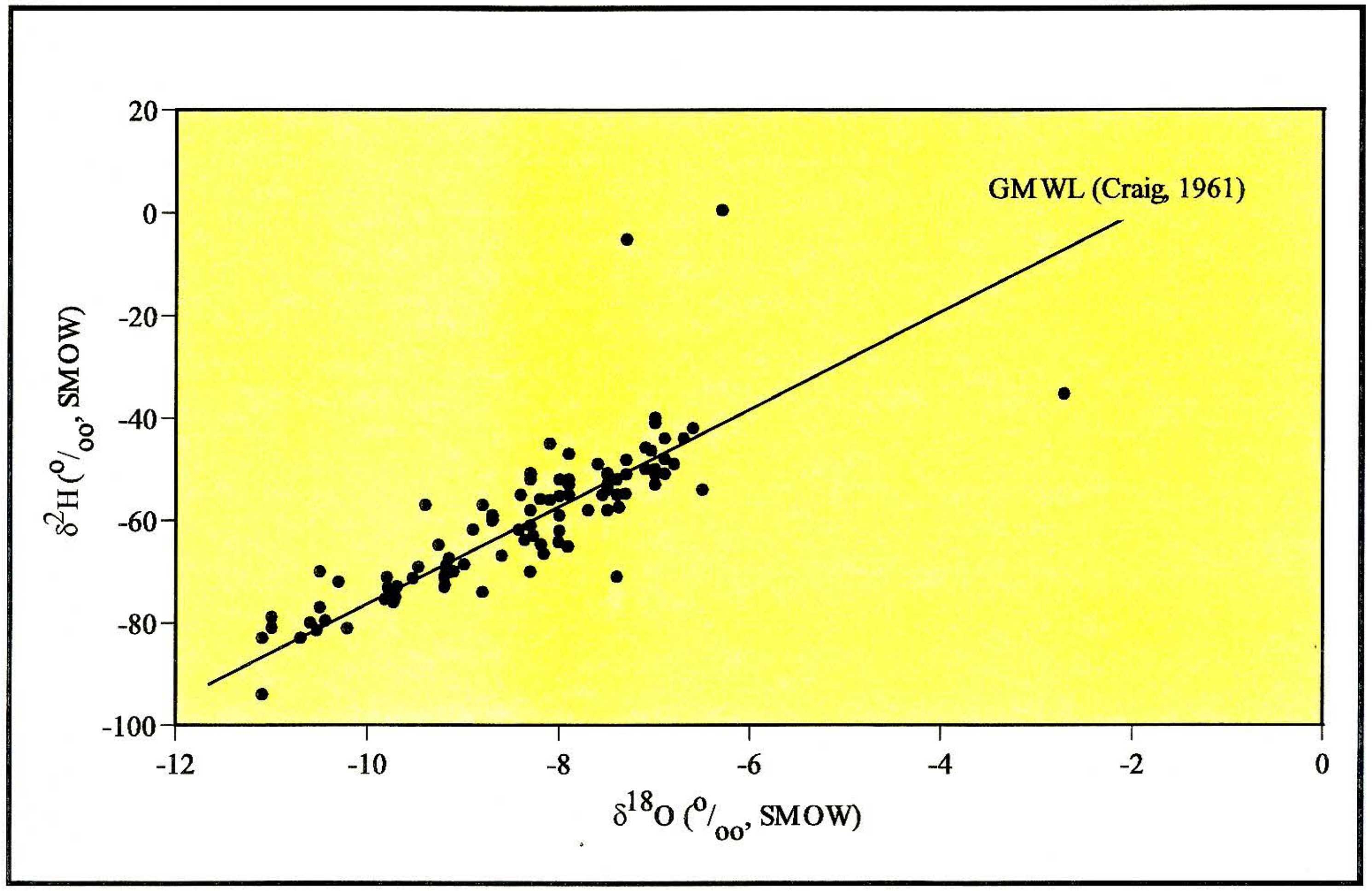
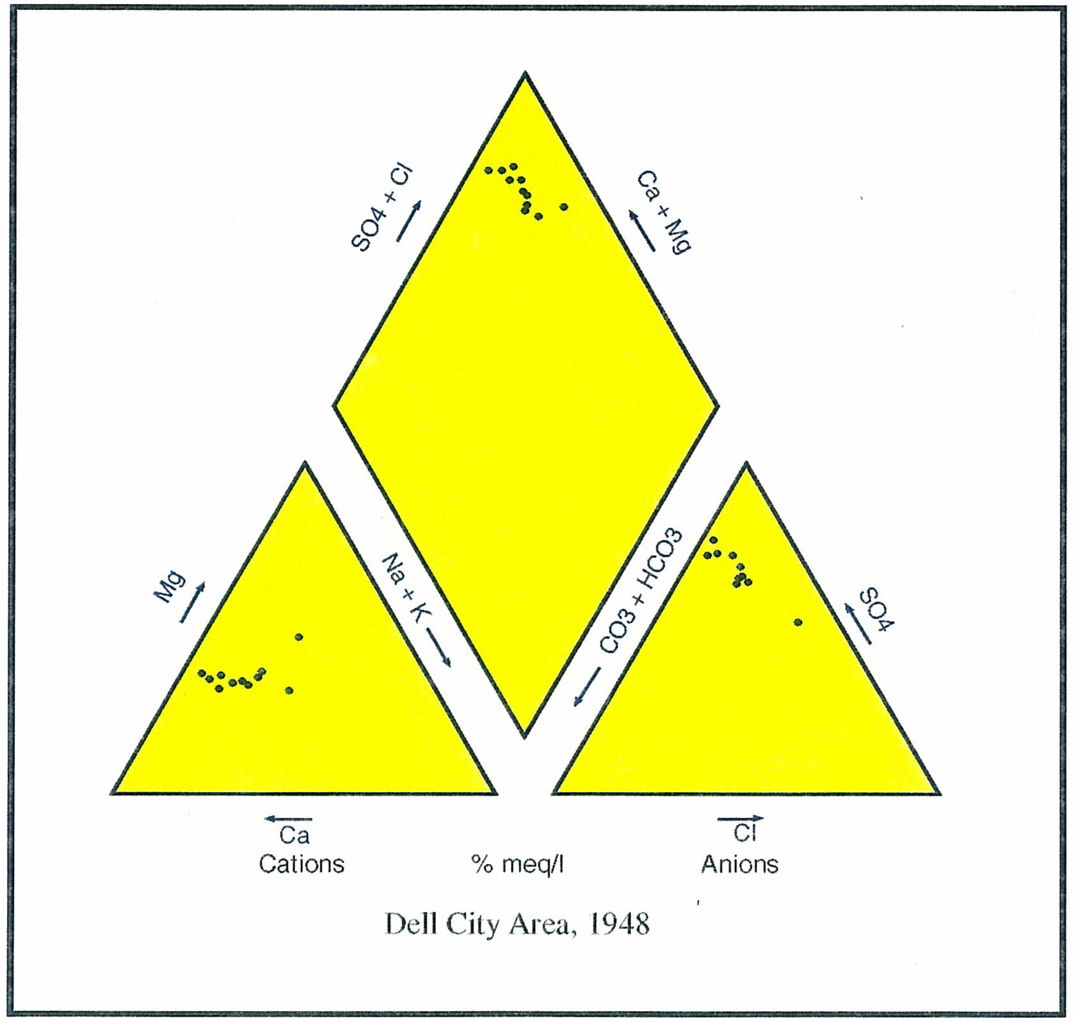


Figure 6.12. Plot of δ^2H vs $\delta^{18}O$ (source of data, Kreitler and others, 1986).



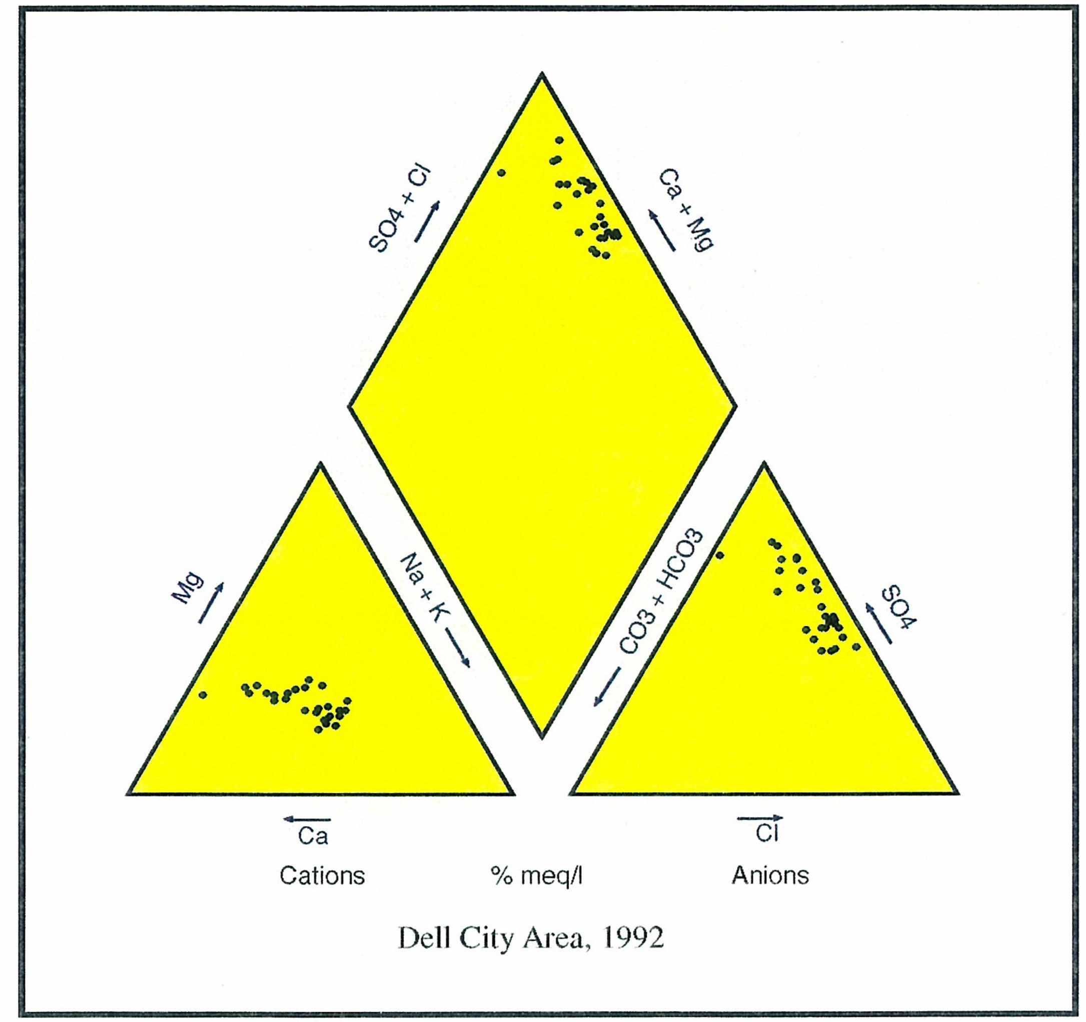


Figure 6.13a. Chemical composition of Dell City ground water in 1948 (source of data, Texas Water Development Board).

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

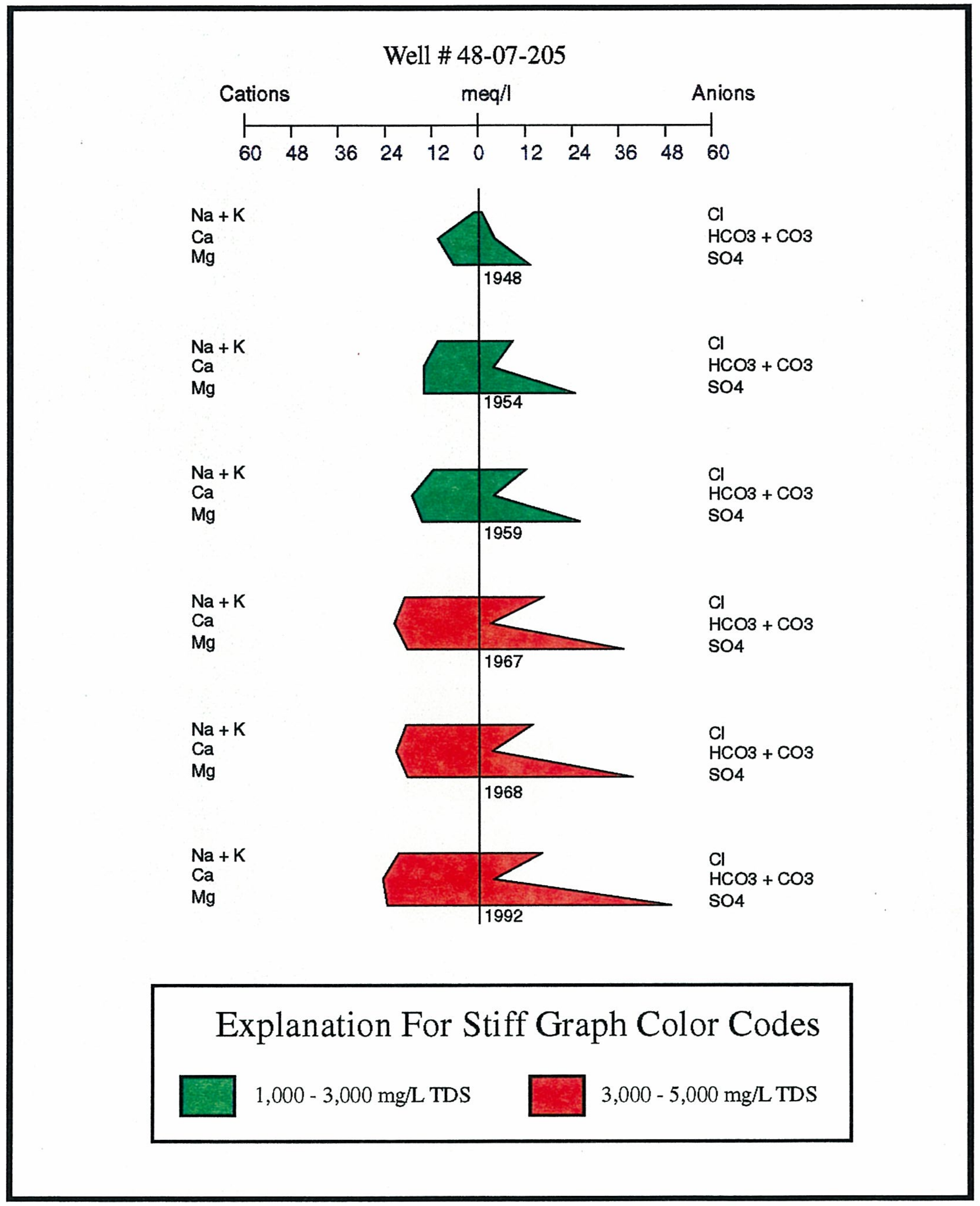


Figure 6.14a. Stiff diagram showing major ion chemistry changes through time in well 48-07-205 (source of data, Texas Water Development Board).

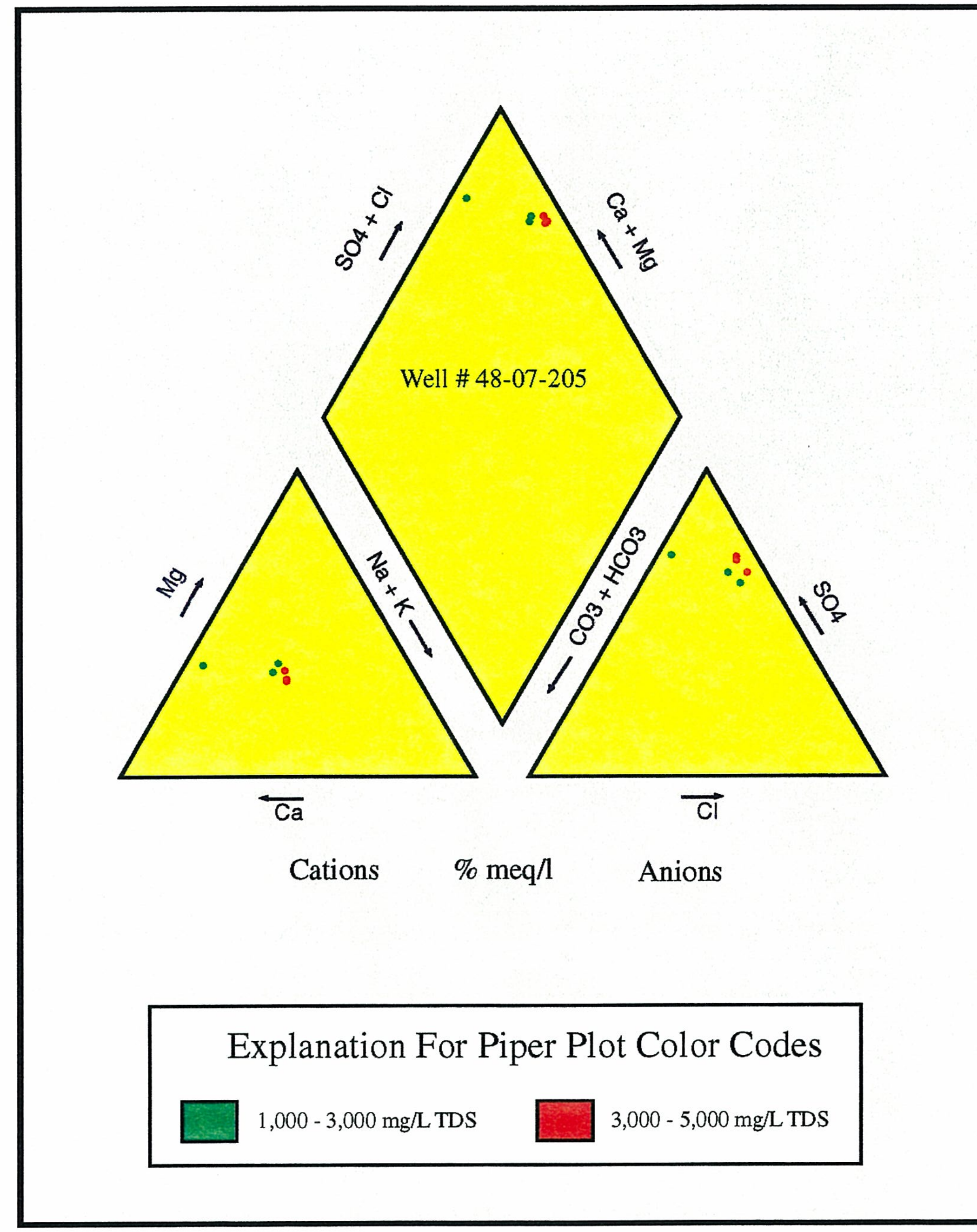


Figure 6.14b. Piper diagram showing major ion chemistry changes in well 48-07-205, also represented in Figure 6.14a (source of data, Texas Water Development Board).

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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Kreitler, C.W., Raney, J.A., Mullican, W.F., Collins, E.W., and Nativ, R., 1987, Geologic and hydrologic studies of sites HU1A and HU1B in Hudspeth County, Texas: Bureau of Economic Geology, Final report prepared for the Texas Low-Level Radioactive Waster Disposal Authority under contract no. IAC (86-87)-1061, 172 p.

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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.

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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.

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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.

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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: 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

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.

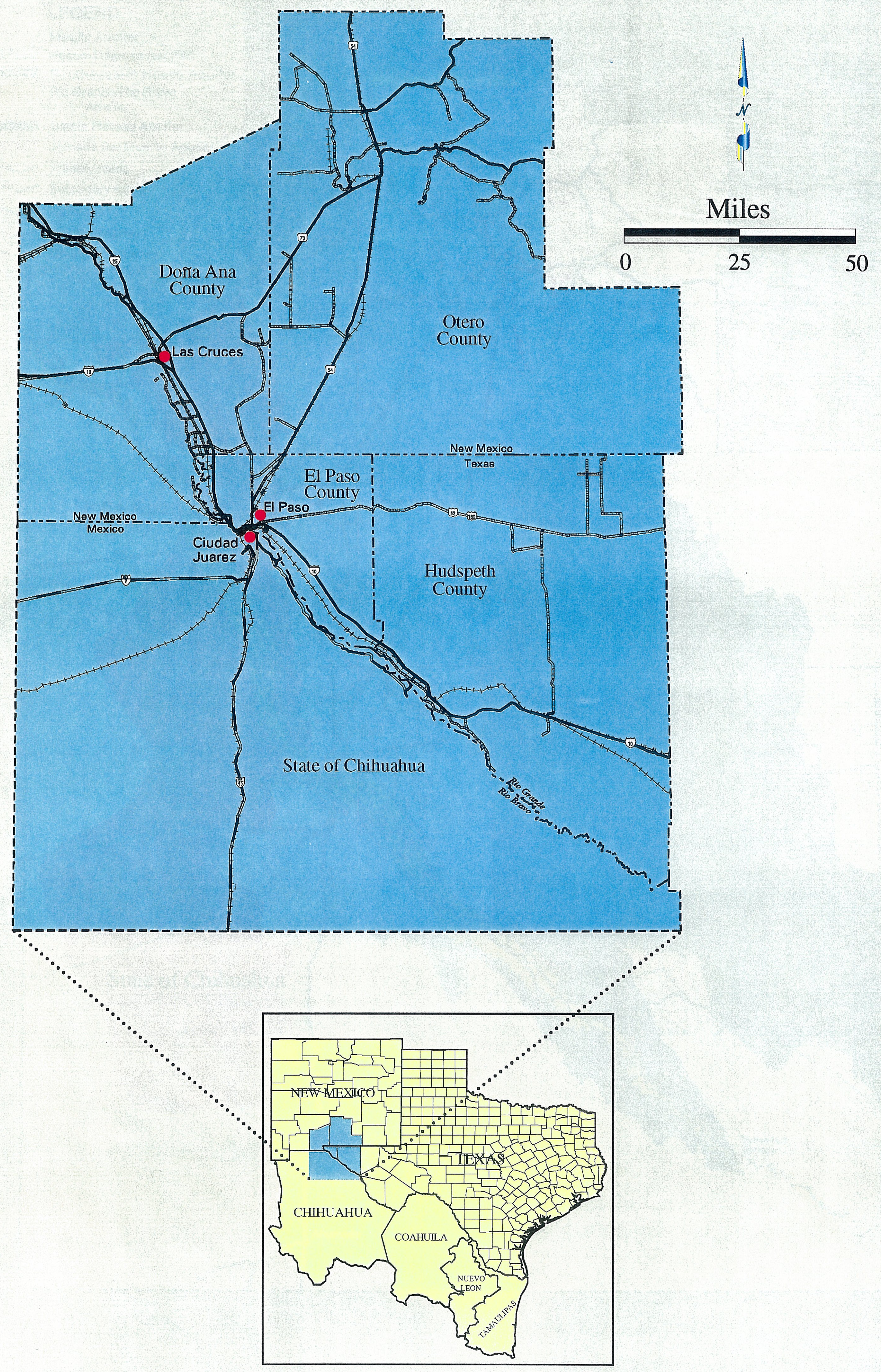
Workbook name:	MEXICO.XLS
Sheet name:	WATER LEVELS (JMAS)
Description:	Contains water level measurements in Ciudad Juarez and surrounding area. Data supplied by Junta Municipal de Agua Y Saneamiento (JMAS).

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).

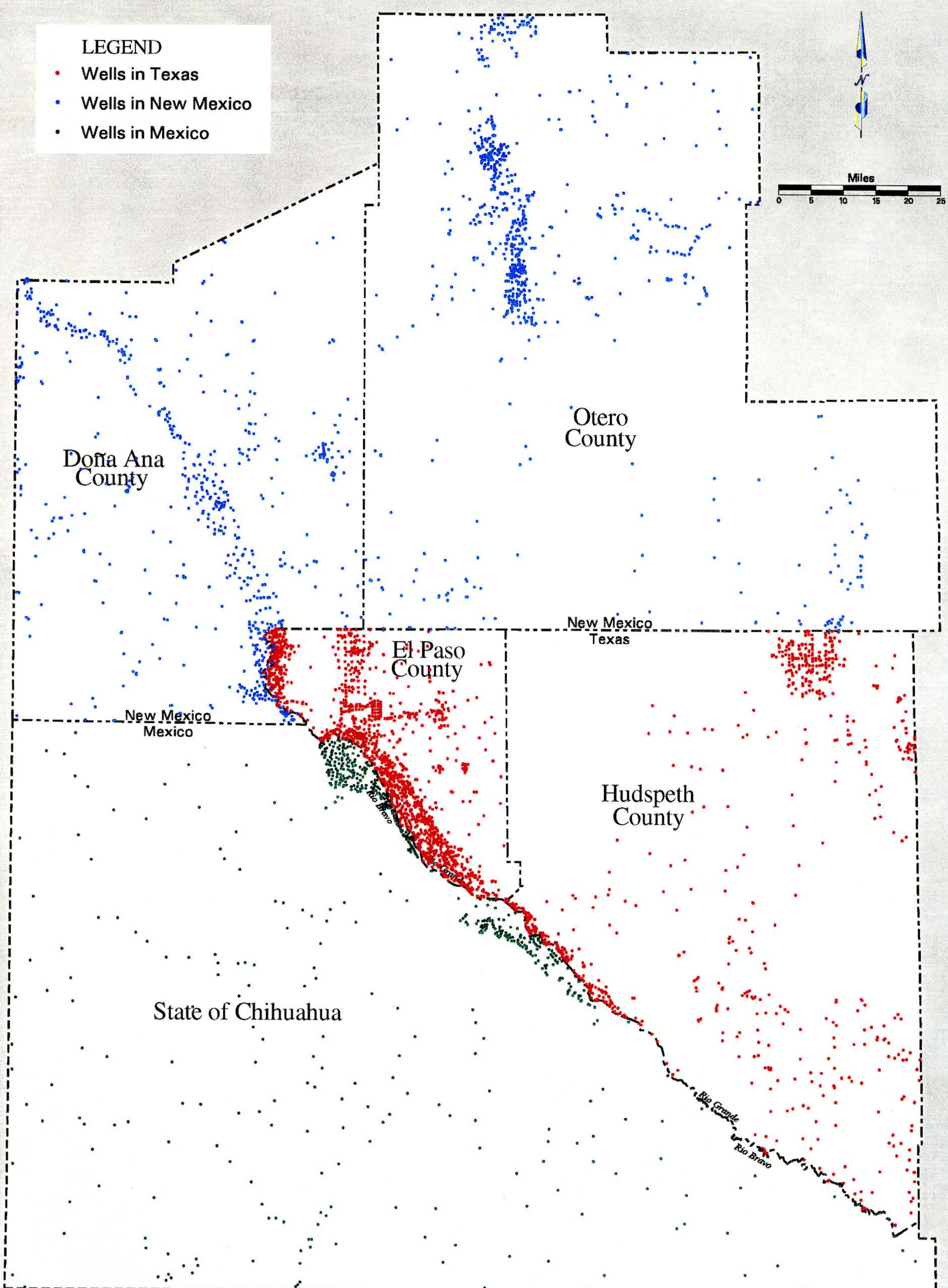
Workbook name:	MEXICO.XLS
Sheet name:	WATER QUALITY (JMAS)
Description:	Contains results of water quality analyses (major ions) for ground water in Ciudad Juarez and surrounding area. Data supplied by Junta Municipal de Agua Y Saneamiento (JMAS).

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).

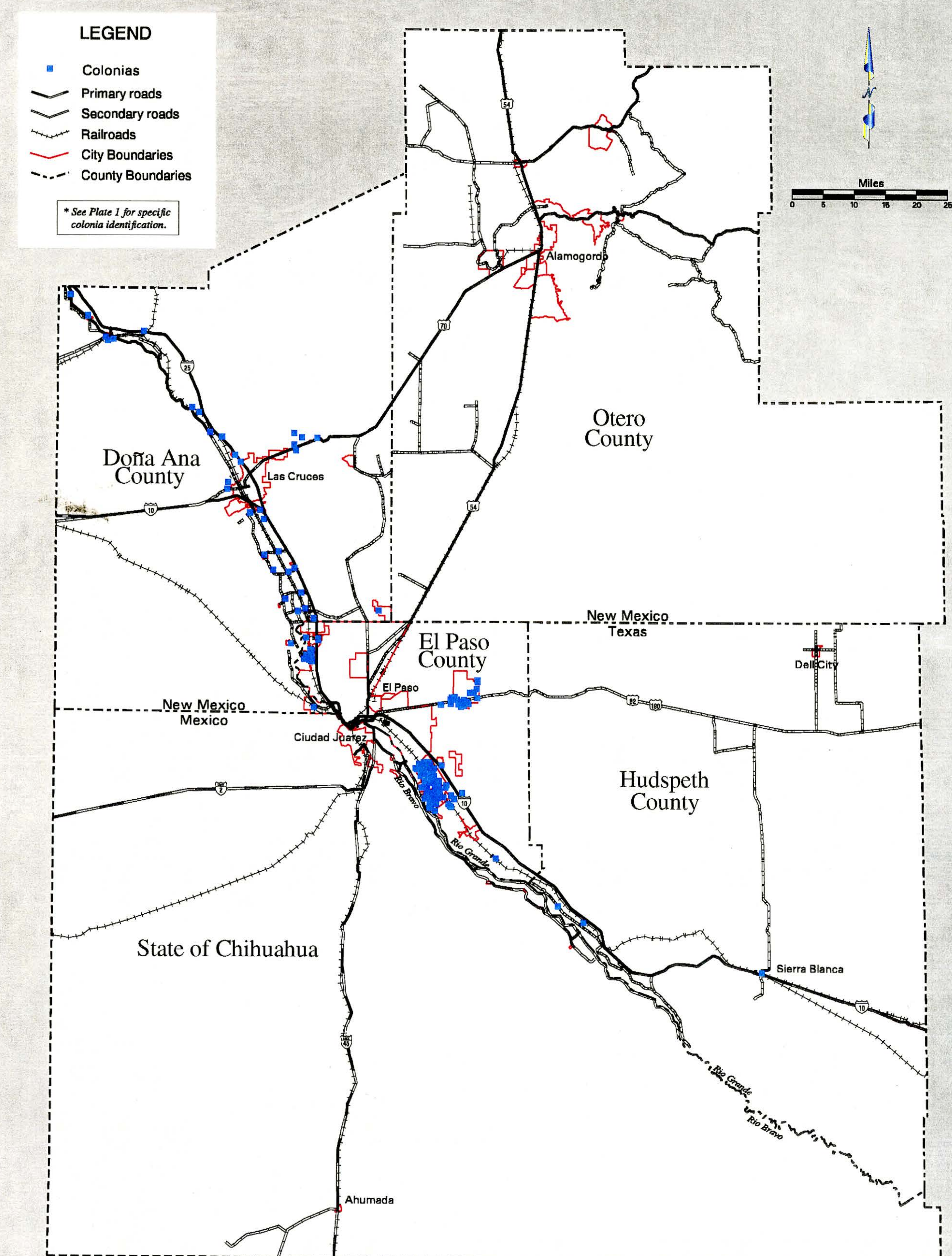
Workbook name:	MEXICO.XLS
Sheet name:	CORE DESCRIPTIONS (CNA)
Description:	Contains lithological descriptions of cores from wells in Juarez Valley. Data supplied by Comision National del Agua (CNA).



LOCATION OF STUDY AREA

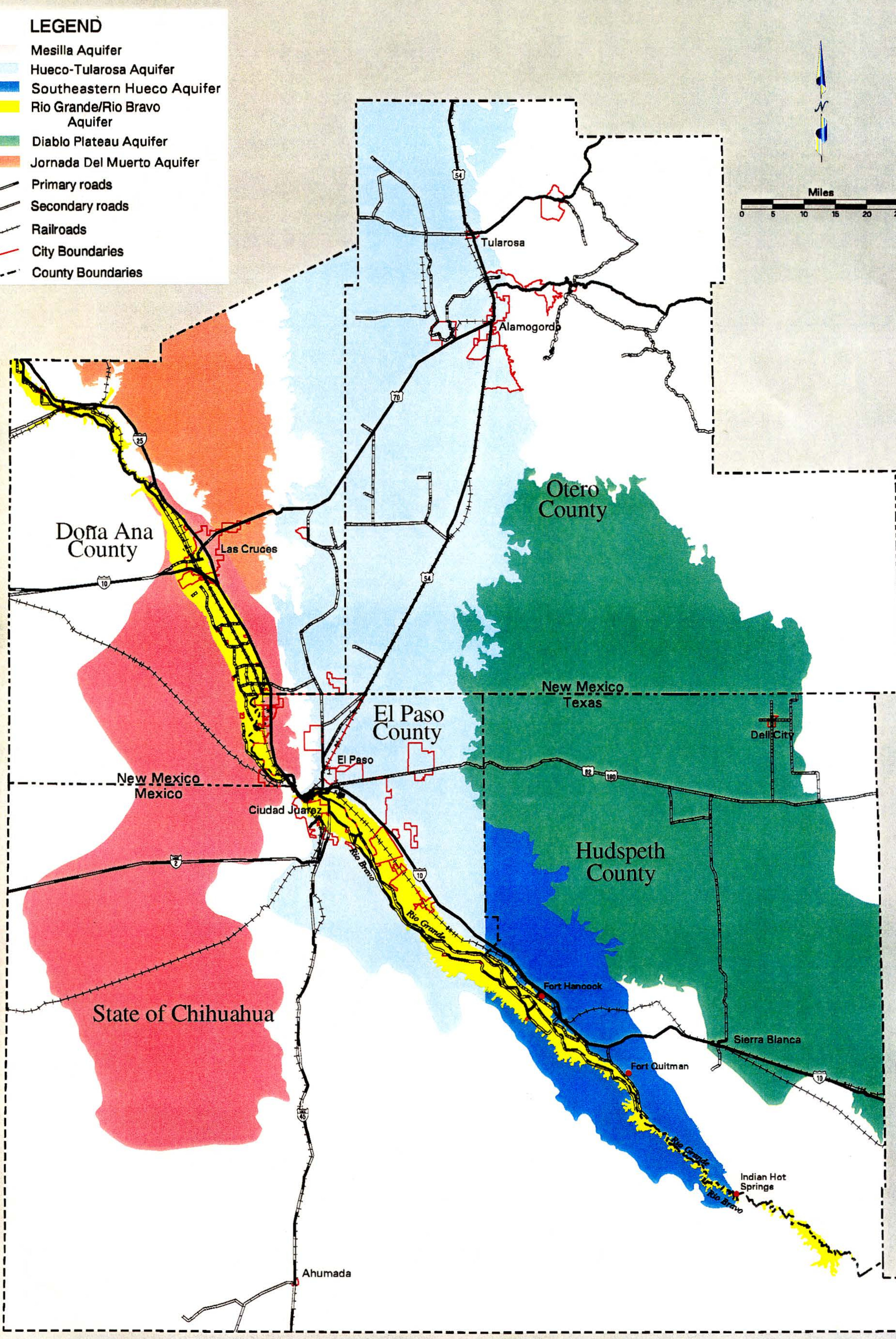


WELL LOCATIONS

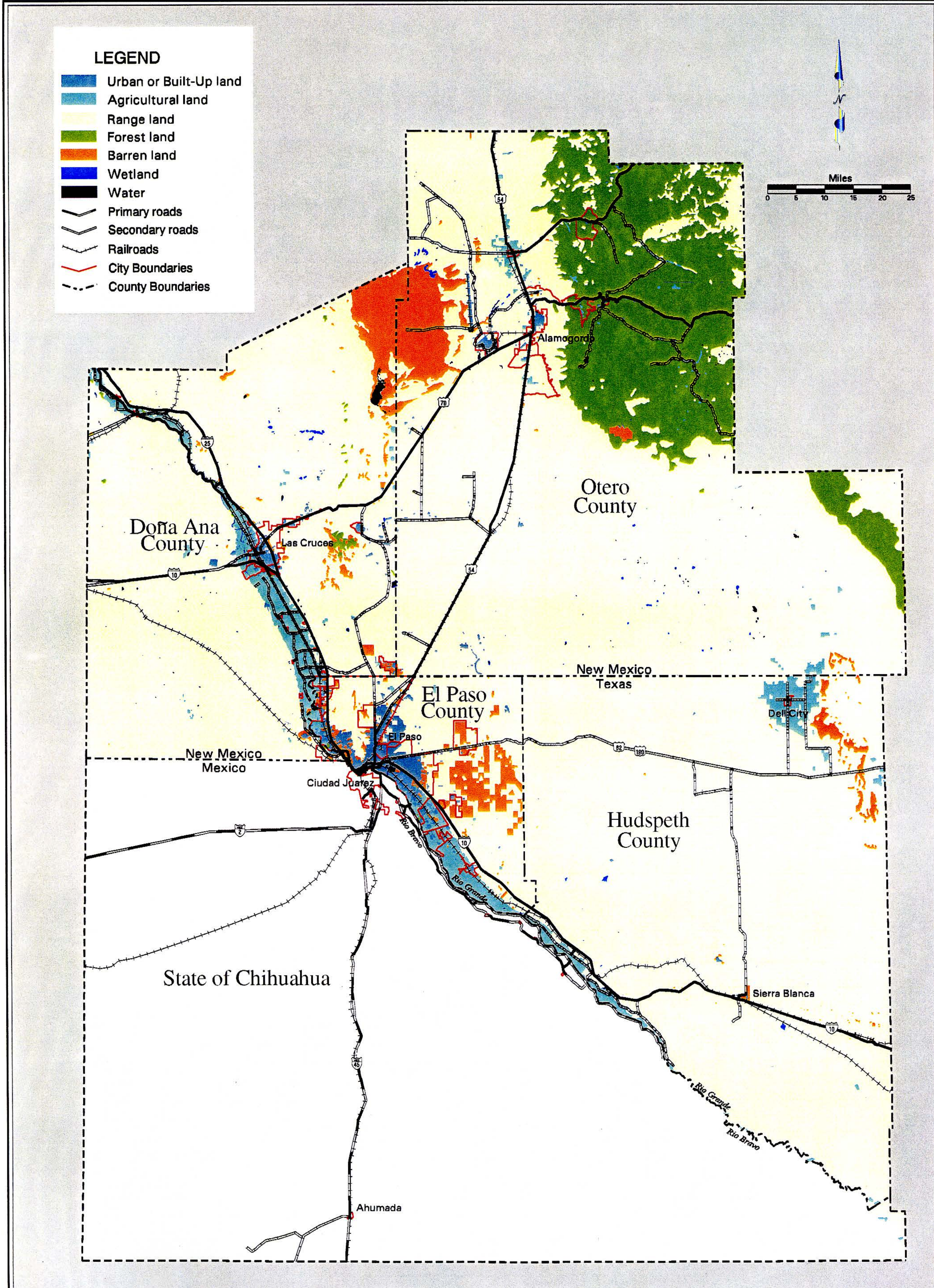


ECONOMICALLY DISTRESSED AREAS

(In the United States)

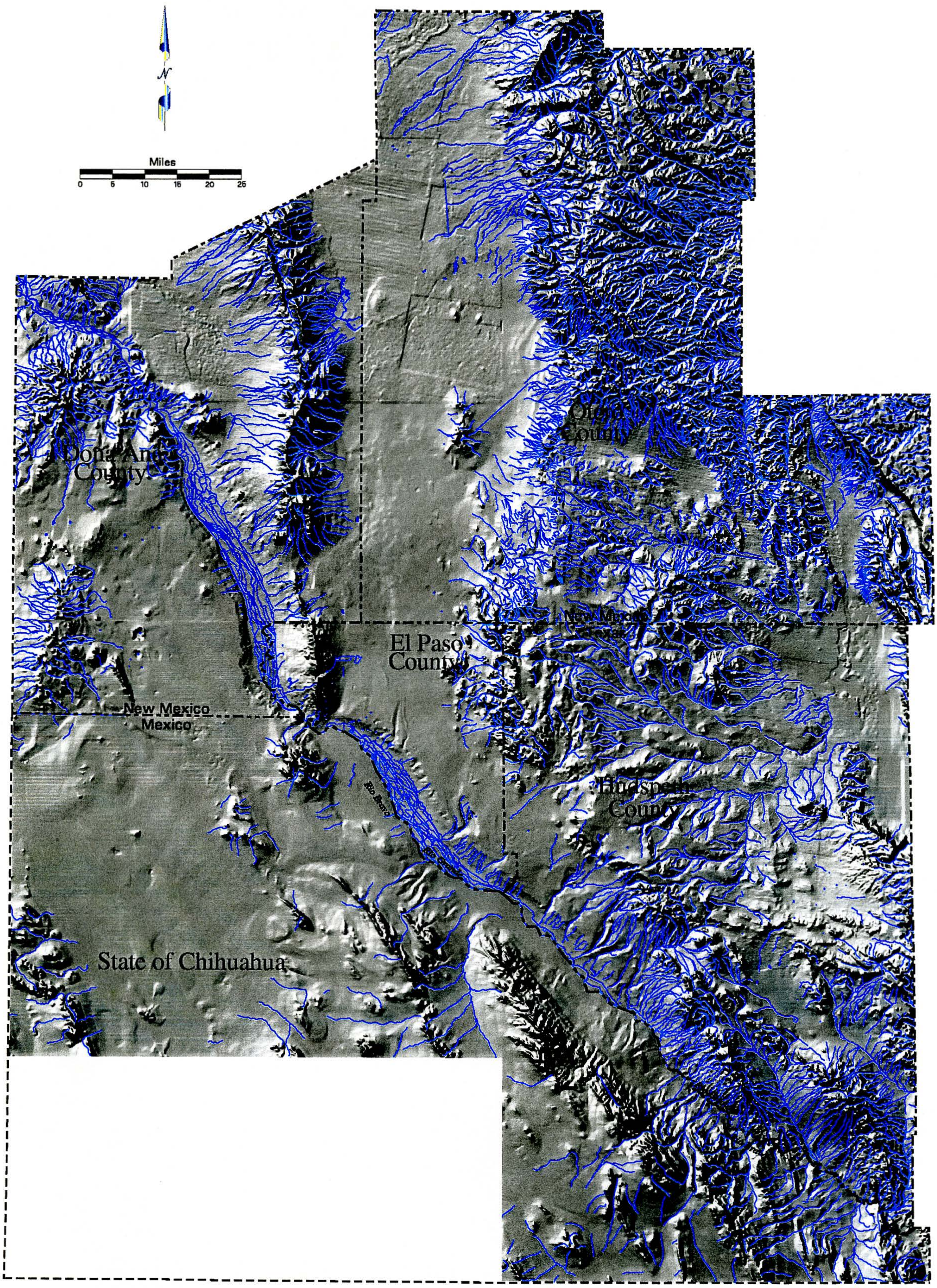


REGIONAL AQUIFERS

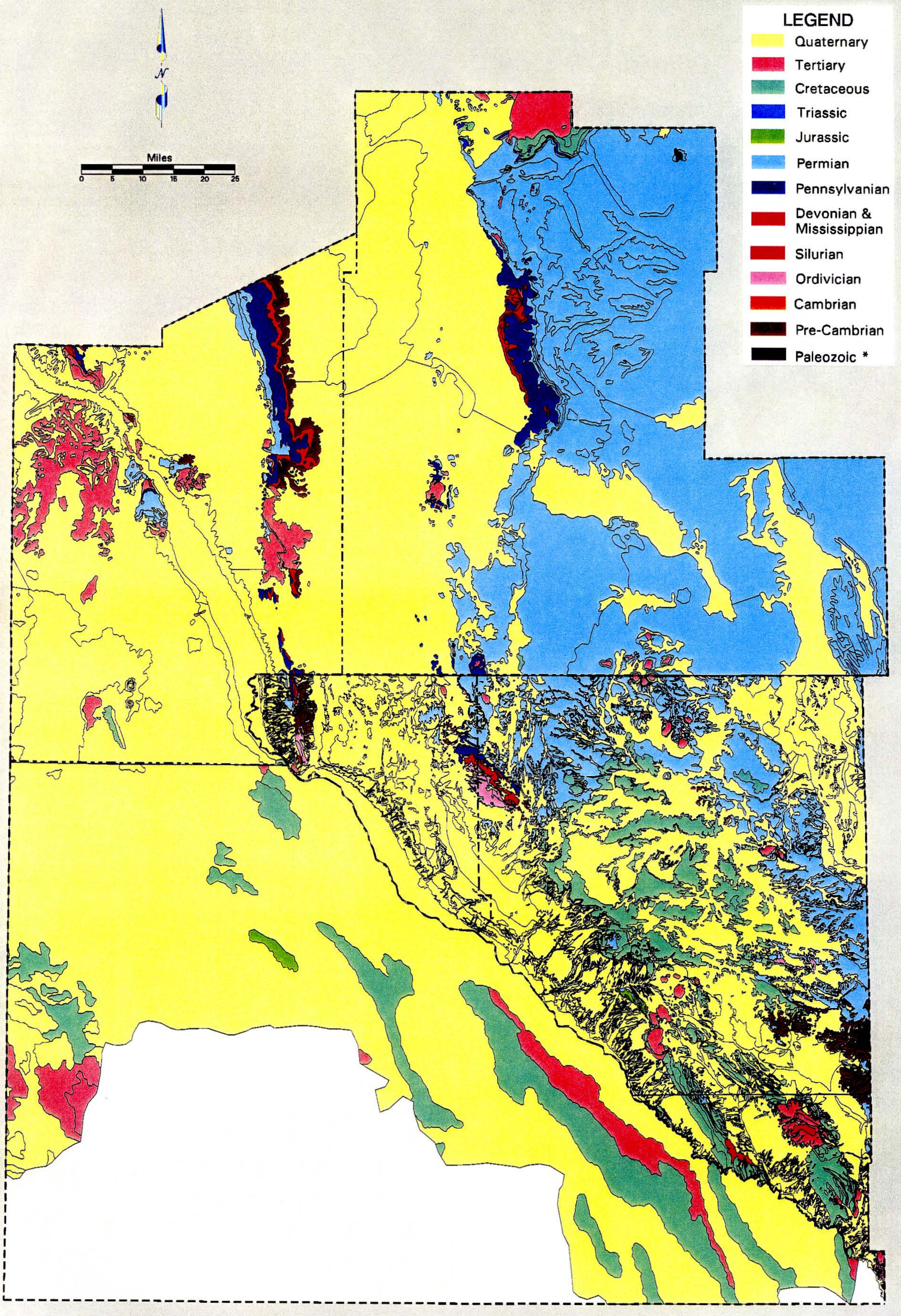


LANDUSE

(In the United States)

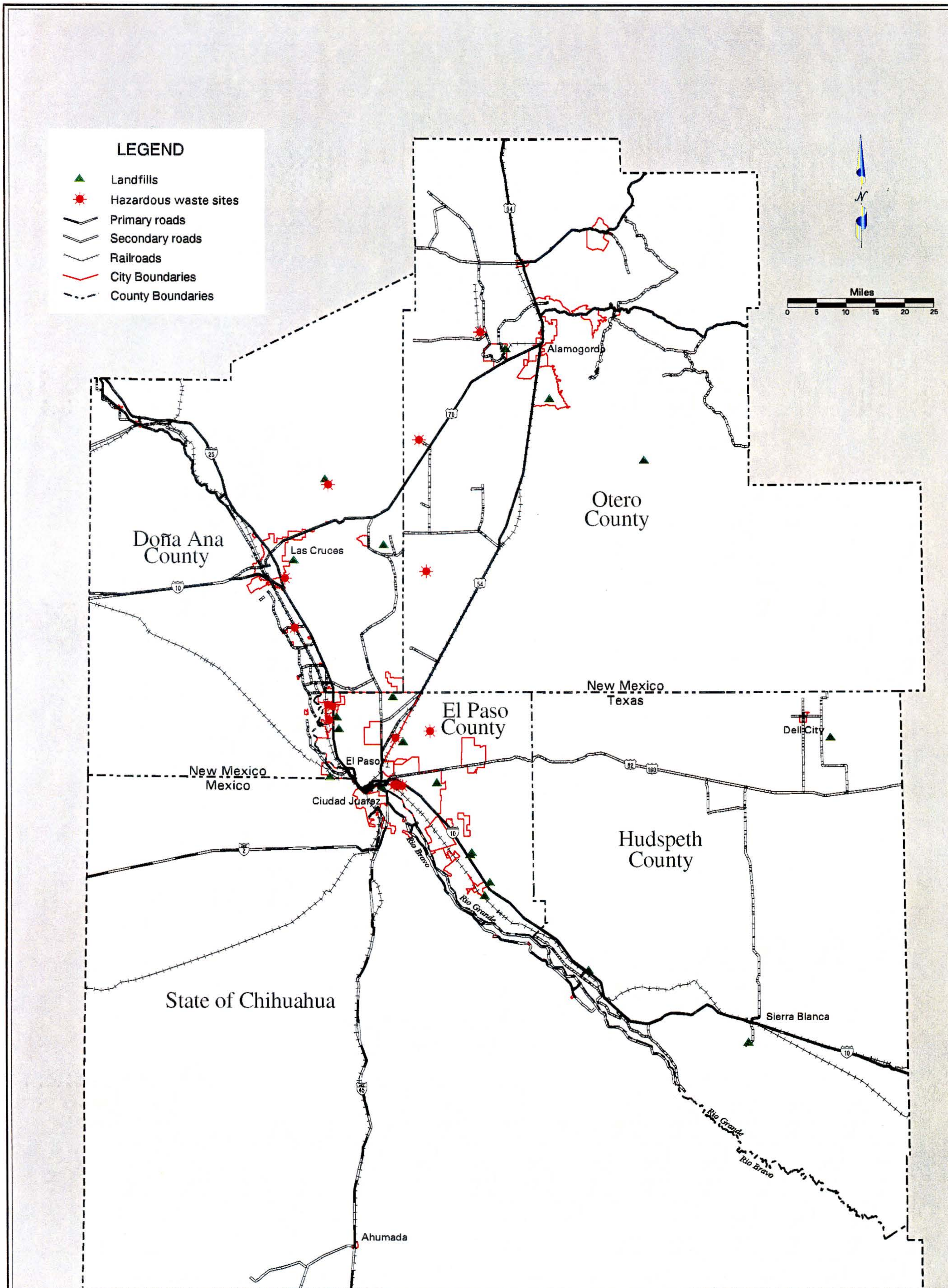


LAND SURFACE RELIEF WITH DRAINAGE



LEGEND
Quaternary
Tertiary
Cretaceous
Triassic
Jurassic
Permian
Pennsylvanian
Devonian & Mississippian
Silurian
Ordivician
Cambrian
Pre-Cambrian
Paleozoic *
Miles
0
5
10
15
20
25
N

GEOLOGY



LANDFILLS AND HAZARDOUS WASTE SITES

(In the United States)