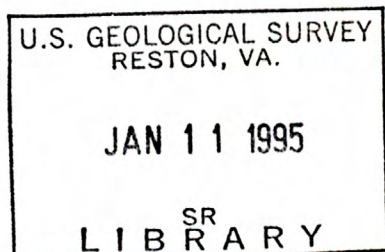


DISSOLVED-SOLIDS CONCENTRATIONS AND HYDROCHEMICAL FACIES IN WATER OF THE EDWARDS-TRINITY AQUIFER SYSTEM, WEST-CENTRAL TEXAS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 93-4126



A contribution of the
Regional Aquifer-System Analysis Program



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By Peter W. Bush, Randy L. Ulery, and Rochelle L. Rittmaster

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**Austin, Texas
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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNIT

| Multiply | By | To obtain |
|---|--------|-----------------------|
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year |
| foot (ft) | 0.3048 | meter |
| foot squared per day (ft ² /d) | 0.0929 | meter squared per day |
| inch (in.) | 25.4 | millimeter |
| inch per year (in/yr) | 25.4 | millimeter per year |
| mile (mi) | 1.609 | kilometer |
| square mile (mi ²) | 2.590 | square kilometer |

Abbreviated water-quality unit

mg/L, milligram per liter

Dissolved-Solids Concentrations and Hydrochemical Facies in Water of the Edwards-Trinity Aquifer System, West-Central Texas

By Peter W. Bush, Randy L. Ulery, and Rochelle L. Rittmaster

Abstract

A major part of the Edwards-Trinity aquifer system contains freshwater, but sizable parts contain marginally fresh or slightly saline water. The predominant hydrochemical facies in the aquifer system is calcium bicarbonate, but at least seven other facies are present in the aquifer system. Each facies has a distinct dissolved-solids range, which accounts for generally similar patterns in the areal distributions of dissolved-solids concentrations and hydrochemical facies in the aquifer system.

The median dissolved-solids concentration in 600 water samples from the Edwards aquifer in the Balcones fault zone is 297 mg/L (milligrams per liter); the interquartile range is 93 mg/L. In the freshwater zone of the Edwards aquifer updip of a freshwater/saline-water transition zone, the water is almost exclusively calcium bicarbonate. In the mostly slightly saline water of the transition zone, calcium sulfate predominates among the analyses.

The median dissolved-solids concentration in 532 water samples from the Trinity aquifer in the Hill Country is 537 mg/L and the interquartile range is 573 mg/L. Areas of slightly saline water are interspersed among areas of freshwater and marginally freshwater throughout the Hill Country. Four bicarbonate and sulfate facies, spread vertically throughout the saturated section, are represented in most of the Hill Country analyses; calcium bicarbonate predominates. Among water samples from the three water-yielding zones of the Trinity aquifer, the median dissolved-solids concentration of water samples is 583 mg/L for the upper Trinity, 510 mg/L for the middle Trinity, and

652 mg/L for the lower Trinity. The dissolved-solids concentrations in water from the middle Trinity zone are (statistically) significantly different from those of the other two zones.

The median concentration of dissolved solids in 2,296 water samples from the Edwards-Trinity aquifer in the Edwards Plateau is 379 mg/L and the interquartile range is 547 mg/L. Freshwater is nearly everywhere except in much of the northwestern part of the subarea, where slightly saline water predominates. Hydrochemical facies are distributed in a similar pattern to dissolved-solids concentrations. Bicarbonate water prevails everywhere except the northwestern part of the subarea, which contains sulfate water and some chloride water.

The most likely sources of sulfate and chloride ions in the northwestern part of the Edwards Plateau are the underlying Dockum aquifer and adjacent Triassic rocks.

The median concentration of dissolved solids in 143 water samples from the Edwards-Trinity aquifer in the Trans-Pecos is 929 mg/L and the interquartile range is 1,626 mg/L. In general, fresher water is in the southeastern part of the Trans-Pecos than in the northwestern part. Calcium bicarbonate water predominates in the southeastern part, and mixed-cation mixed-anion and calcium sulfate facies are the most common in the northwestern part of the Trans-Pecos. Adjacent aquifers are probable sources of sulfate and chloride ions.

INTRODUCTION

The Edwards-Trinity aquifer system is a sequence of near-surface, hydraulically connected, carbonate and quartzose clastic rocks of Cretaceous age that underlies about 42,000 mi² of west-central Texas (fig. 1). The aquifer system is one of 28 aquifer systems nationwide identified for study as a part of the Regional Aquifer-System Analysis (RASA) program of the U.S. Geological Survey. The RASA projects are intended to define the regional hydrogeology of major aquifer systems and establish a framework of geologic, hydrologic, and geochemical information that can be used for regional assessment of ground-water resources and in support of local studies (Sun, 1986, p. 6).

This report describes the distributions of dissolved-solids concentrations and hydrochemical facies in water of the Edwards-Trinity aquifer system. The report discusses the potential sources of some of the chemical constituents that account for the facies characterizing the water. For the purposes of this discussion, the aquifer system is divided into four geographic subareas. Where the system comprises more than one aquifer in a subarea, the description pertains to the principal aquifer. The descriptions include characteristics of the contiguous, hydraulically connected, freshwater/saline-water transition zone southeast of the aquifer system.

HYDROGEOLOGY

The aquifer system comprises three aquifers and two confining units (fig. 2). The aquifers are the Edwards, the Trinity, and the Edwards-Trinity. These aquifers are laterally adjacent except in the southeastern part of the area, where the coastward dip of the units steepens and part of the Trinity aquifer extends beneath the Edwards aquifer. The confining units of the system are the Navarro-Del Rio, which directly overlies the downdip part of the Edwards aquifer, and the Hammett, which is within the Trinity aquifer updip of the Edwards aquifer and within the southeastern part of the Edwards-Trinity aquifer. The northwestern margin of the Edwards-Trinity aquifer is directly overlain by two major aquifers, the Cenozoic Pecos alluvium and the High Plains, in rocks of Cenozoic age and Tertiary age, respectively.

The coastward extent of freshwater flow in the aquifer system is limited by a freshwater/saline-water transition zone (fig. 2) of slightly to moderately saline

water (1,000 to 10,000 mg/L dissolved-solids concentration). Transmissivity in the transition zone is much smaller than that of the adjacent freshwater zone.

Part of the Edwards-Trinity aquifer system is underlain by parts of three minor aquifers, the Dockum, the Rustler, and the Capitan (fig. 3). The Dockum aquifer is in rocks of Triassic age and the Rustler aquifer and Capitan aquifer are in rocks of Permian age.

The four geographic subareas of the aquifer system are the Balcones fault zone, the Hill Country, the Edwards Plateau, and the Trans-Pecos (fig. 4). The Balcones fault zone is defined in this report as being coincident with the area where the Edwards is the principal aquifer. The Hill Country coincides with the area where the Trinity is the principal aquifer. Although the Trinity exists beneath the Edwards in the Balcones fault zone, it is not the principal aquifer there. The Edwards Plateau and the Trans-Pecos together are coincident with the area of the Edwards-Trinity aquifer. The two geographic subareas are separated by the Pecos River. The southeastern part of the Trans-Pecos is a region known as the Stockton Plateau (Fenneman, 1931, p. 47). The northwestern part of the Trans-Pecos is generally coincident with the southern part of a region known as the Toyah basin (Fenneman, 1931, p. 48).

Several stratigraphic units of varied lithology compose the principal aquifer in each of the four geographic subareas (Barker and others, 1994) (pl. 1). The carbonate rocks composing the Edwards aquifer in the Balcones fault zone are extensively fractured and dissolutioned limestone, dolomitic limestone, and dolostone. In the adjacent, negligibly dissolutioned freshwater/saline-water transition zone, sulfate minerals are prevalent in addition to carbonates. The Trinity aquifer in the Hill Country commonly is divided into three water-yielding zones; the upper Trinity (upper part of the Glen Rose Limestone), the middle Trinity (lower part of the Glen Rose Limestone, Hensel Sand, and Cow Creek Limestone), and the lower Trinity [Sycamore Sand (updip), Sligo Formation, and Hoston Formation (downdip)]. The upper part of the Glen Rose is mostly a thin-bedded sequence of marls, dolomitic mudstones and limestones, and some bedded anhydrite. The middle Trinity formations are primarily sandy, fossiliferous limestone and dolostone with interbedded marl, clay, shale, sand, and evaporite. The updip part of the lower Trinity aquifer is a sequence of clastic detritus that grades into dolostone, limestone, sandstone, and evaporite downdip. The Edwards-Trinity aquifer in the Edwards Plateau and the Trans-Pecos

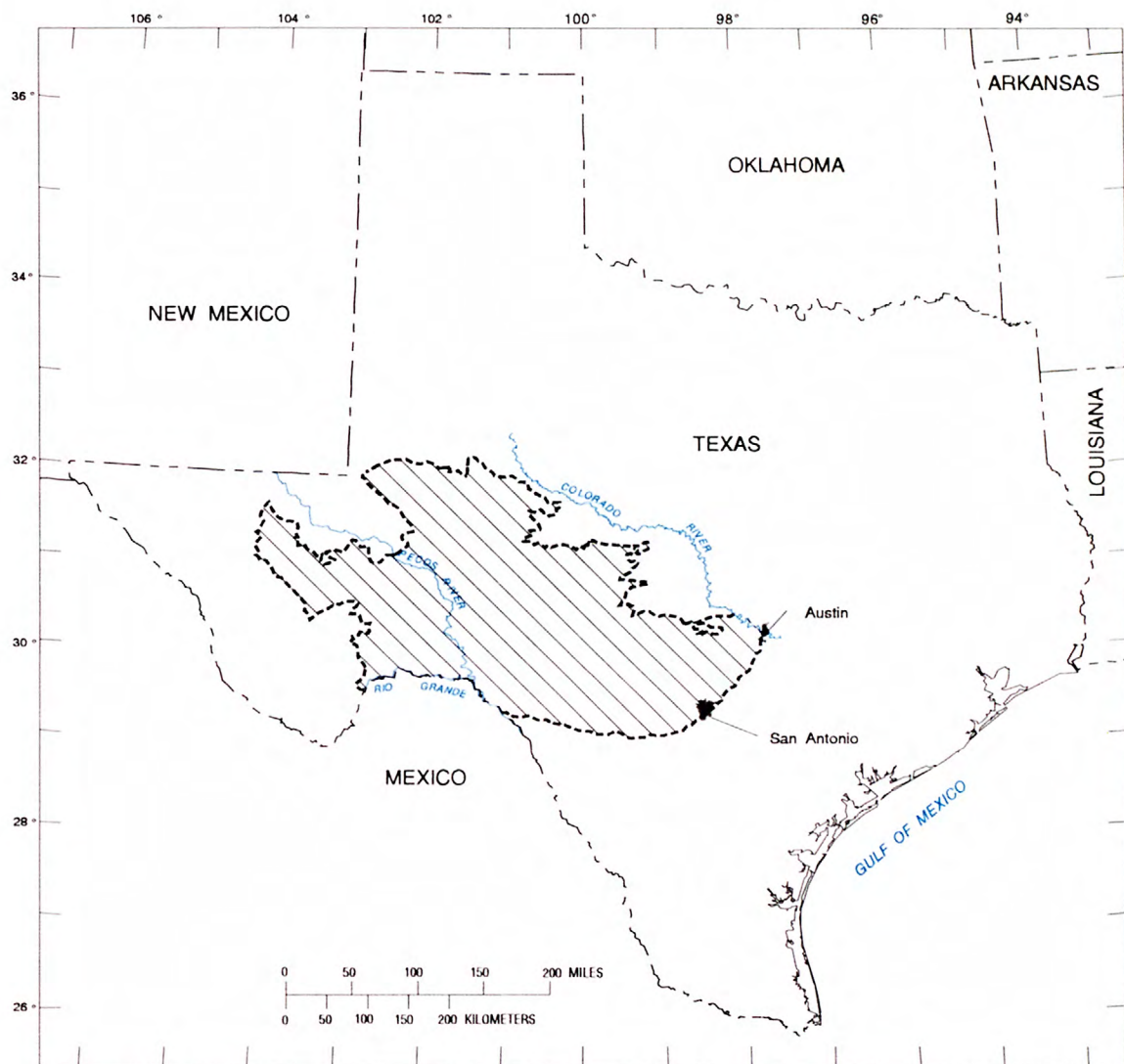


Figure 1. Location of the Edwards-Trinity aquifer system, west-central Texas.

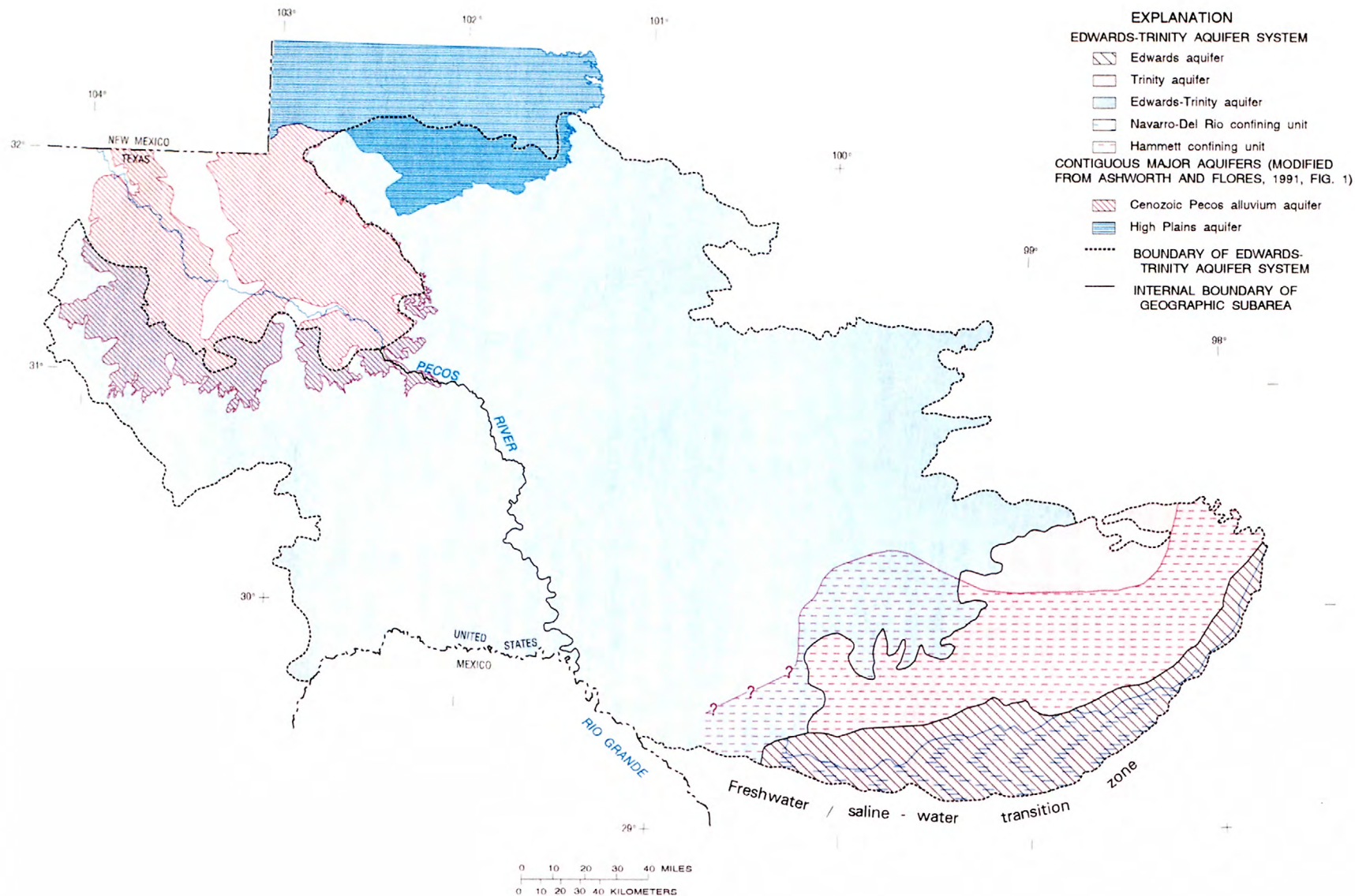


Figure 2. Aquifers and confining units of the Edwards-Trinity aquifer system and contiguous major aquifers.

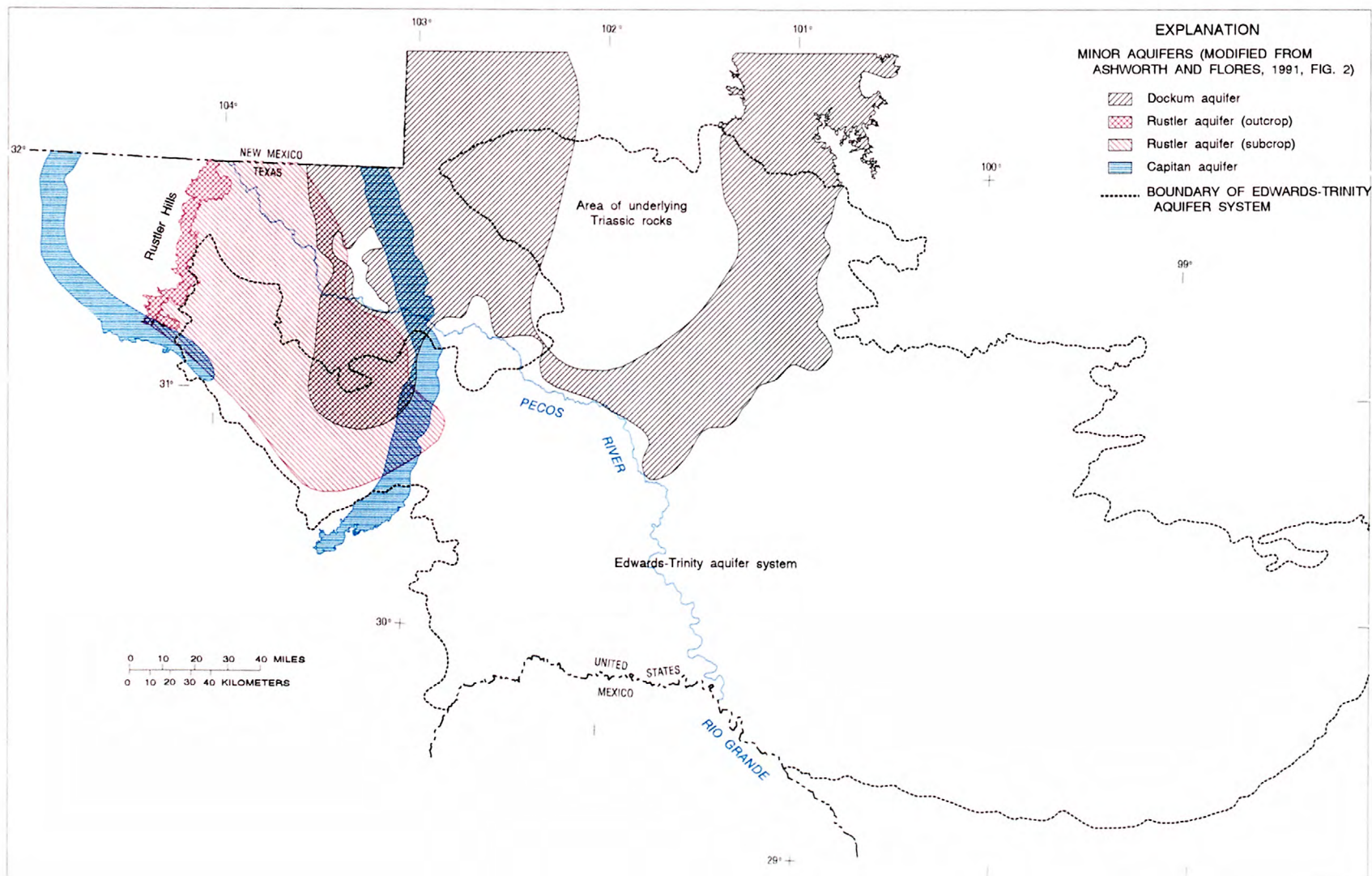


Figure 3. Selected minor aquifers underlying the Edwards-Trinity aquifer system.

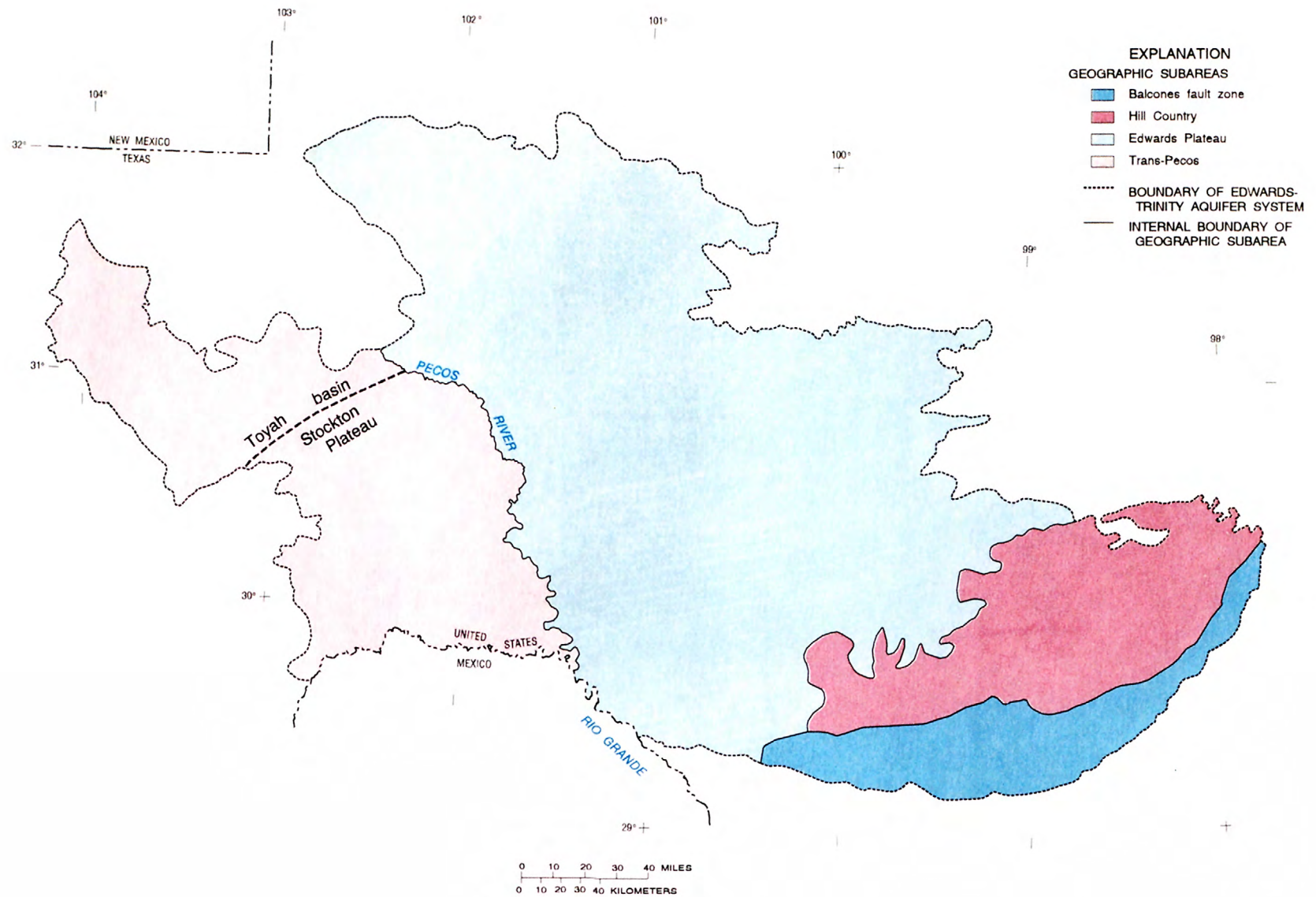


Figure 4. Geographic subareas of the Edwards-Trinity aquifer system.

is composed of mostly limestone and dolostone in its upper part (Washita and Fredericksburg Groups); and predominantly quartz-rich sand and sandstone, with limestone, marl, clay, shale, and evaporite in places in its lower part (Trinity Group).

The uppermost saturated zones of the principal aquifers of the Edwards-Trinity aquifer system are unconfined, or nearly so, except in the Balcones fault zone beneath the Navarro-Del Rio confining unit. The depth to the saturated zone in unconfined areas is less than 200 ft over much of the aquifer system, but ranges from 200 to 400 ft in the south-central part of the Edwards Plateau, and is as much as 800 ft in the south-eastern part of the Trans-Pecos.

The flow system in the Edwards aquifer is considerably different from that in the Trinity and the Edwards-Trinity aquifers. Post-Cretaceous, normal faulting disrupted the rocks in the Balcones fault zone. The faulting created avenues for water to flow into the shallow carbonate rocks and dissolve the more soluble constituents, thus enhancing the development of permeability. Consequently, transmissivity in the Edwards aquifer in the Balcones fault zone probably averages about 750,000 ft²/d (Maclay and Land, 1988, p. A26), and the flow system in the Edwards is dynamic and vigorous; transmissivity in the Trinity aquifer in the Hill Country, and in the Edwards-Trinity aquifer in the Edwards Plateau and the Trans-Pecos, probably averages less than 10,000 ft²/d, and the flow system in those aquifers is relatively sluggish. Transmissivity in the freshwater/saline-water transition zone probably averages less than 1,000 ft²/d, and flow is minimal.

The eastern area of the aquifer system is more humid than the western area. For 1951-80, average annual rainfall in the Balcones fault zone was about 28 in.; in the Hill Country, about 30 in.; in the Edwards Plateau, about 19 in.; and in the Trans-Pecos, about 13 in. Correspondingly, recharge is greater in the eastern part of the area than in the western part. The source of most recharge to the Edwards aquifer is leakage from streams crossing the northern margin of the Balcones fault zone. The long-term (1934-89) average of this component of total recharge to the Edwards aquifer is estimated to be 628,000 acre-ft/yr (Nalley and Thomas, 1990, p. 14). For comparison, 628,000 acre-ft/yr is equivalent to about 4 in/yr over the Balcones fault zone. Computer simulation of flow in the aquifer system (Kuniansky and Holligan, 1994) shows that recharge to the Trinity aquifer ranges from 1 to 2 in/yr in most of the Hill Country; recharge to the Edwards-

Trinity aquifer is less than 0.5 in/yr in most of the relatively arid Edwards Plateau and the Trans-Pecos.

DATA BASE AND MAP PREPARATION

The data base from which the maps of dissolved-solids concentrations and hydrochemical facies (pl. 2) were made consists of 3,571 analyses of water samples from 3,571 wells. Six hundred analyses are for water samples from the Balcones fault zone and the adjacent freshwater/saline-water transition zone (hereafter referred to collectively as the Balcones fault zone), 532 are from the Hill Country, 2,296 are from the Edwards Plateau and the adjacent freshwater/saline-water transition zone (hereafter referred to collectively as the Edwards Plateau), and 143 are from the Trans-Pecos. The source of about half of the analyses in the Balcones fault zone is the water-quality data base of the U.S. Geological Survey, and the source of the other half is the water-quality data base of the Texas Water Development Board. In the other geographic subareas, virtually all of the analyses are from the data base of the Texas Water Development Board. The years of sample collection range from 1936 to 1986; the median year is 1969 and about one-half of the samples were collected from 1966 through 1975.

The 3,571 analyses in the data base were selected from more than 7,000 available analyses. Analyses of water from wells without State identification numbers were excluded from the data base. Because the specific depth intervals from which samples were collected are unknown, the aquifer or zone represented by a sample must be assumed based on a State aquifer code assigned at the time of collection. Thus, analyses without State aquifer codes were excluded from the data base. Analyses in which the milliequivalent sums of cations (calcium + magnesium + sodium + potassium) and anions (bicarbonate + sulfate + chloride + fluoride + nitrate) did not balance within 5 percent were excluded from the data base. Nearly 1,000 wells had multiple analyses, the number of which ranged from 2 to 21, with a median of 3. From each set of multiple analyses, the most recent analysis with the most data was retained for the data base. Dissolved-solids concentration was computed as the sum of major dissolved constituents [calcium + magnesium + sodium + potassium + (0.4917 x bicarbonate) + sulfate + chloride + fluoride + nitrate + silica]. In the computation of dissolved solids, the bicarbonate ions in solution generally

are converted to carbonate in the solid phase, as indicated by the multiplication factor (Hem, 1985, p. 157).

The areal density of sampled wells and the range in concentrations of constituents is substantial in some places. For this reason, in areas where the density of sampled wells is more than one per 25 mi², the map of dissolved-solids concentrations (pl. 2) is based on median dissolved-solids concentration. Using a computerized geographic information system, a grid of 5-mi by 5-mi blocks was intersected with a map of the 3,571 sampled well locations. Well locations and corresponding analyses thus were associated with grid blocks. The median dissolved-solids concentration was assumed to represent the grid block. The number of analyses in each of the 978 grid blocks with analyses ranged from 1 to 44; about two-thirds of the blocks had more than one analysis.

The map of hydrochemical facies (pl. 2) also was developed using the analysis having the median dissolved-solids concentrations. Back (1960; 1961) introduced the concept of hydrochemical facies to describe or classify the chemical character of ground water. A facies classification characterizing the water in an aquifer is named for the cation and anion that account for at least 50 percent of the total equivalent concentrations of cations and anions, respectively. For example, if calcium accounts for the major fraction of cations and bicarbonate accounts for the major fraction of anions, then the facies describing the water would be calcium bicarbonate. If no single cation or anion accounts for 50 percent of their respective total equivalent concentrations, then the cation or anion facies would be designated as mixed. For example, if more than 50 percent of the cation equivalent concentration is calcium but no single anion accounts for more than 50 percent of the anion equivalent concentration, then the facies describing the water would be calcium mixed. A calcium mixed facies can be made more descriptive by adding the name of the anion that accounts for the largest fraction of the anion equivalent concentration. If, in the previous example, bicarbonate accounts for 40 percent of the anion equivalent concentration and 40 percent is the largest fraction among the anions in solution, then the facies descriptor would be calcium mixed, bicarbonate predominant. Similarly, if the largest cation equivalent concentration of a water sample was 40 percent calcium and the largest anion equivalent concentration was 65 percent bicarbonate, then its facies would be mixed bicarbonate, calcium predominant.

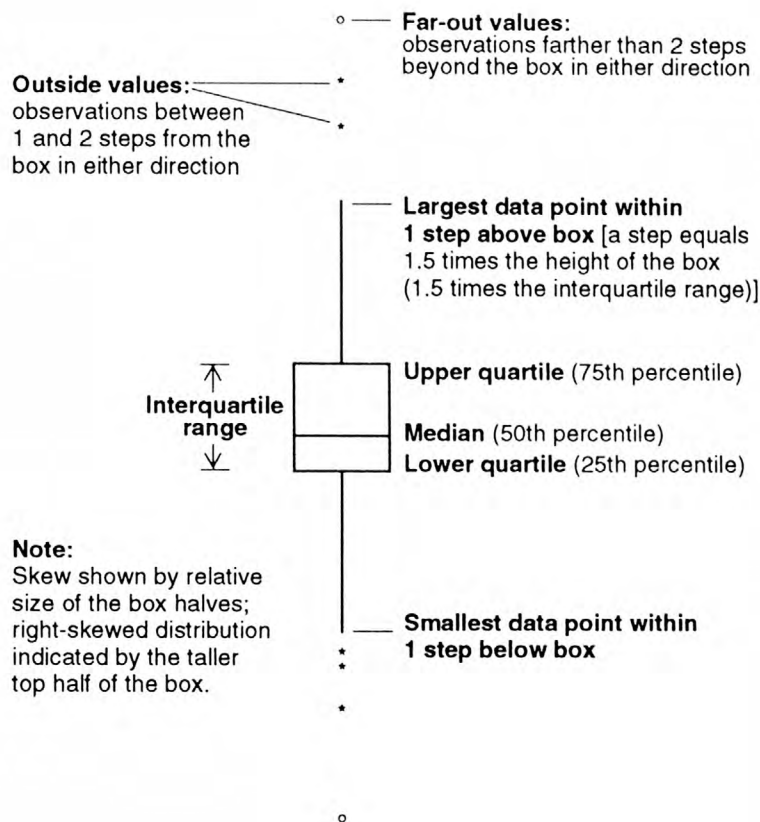
For the 978 median analyses, 24 different facies were identified. To simplify the map of plate 2, similar facies were combined to reduce the number of facies categories on the map to eight. For example, the calcium bicarbonate facies shown on the map actually comprises three facies: (1) calcium bicarbonate, (2) calcium mixed, bicarbonate predominant, and (3) mixed bicarbonate, calcium predominant; the sodium sulfate facies comprises (1) sodium sulfate, (2) sodium mixed, sulfate predominant, and (3) mixed sulfate, sodium predominant; and so forth.

DISSOLVED-SOLIDS CONCENTRATIONS AND HYDROCHEMICAL FACIES

The map of dissolved-solids concentrations in water of the Edwards-Trinity aquifer system (pl. 2) shows that a major part of the system contains fresh-water, but sizable parts contain marginally fresh or slightly saline water; and small parts contain moderately saline water. For aesthetic reasons, the U.S. Environmental Protection Agency (1990, p. 43) has set a (nonenforceable) limit of 500 mg/L on dissolved-solids concentration in public water supplies. The Texas Department of Health [1977 (revised 1990), p. 25] enforces a limit of 1,000 mg/L (but not if alternate supplies are unavailable at a reasonable cost). The map shows that neither standard is met in some places, especially the northwestern parts of the Edwards Plateau and the Trans-Pecos. The suitability of water for public supply and other purposes also depends on concentrations of certain individual constituents.

The map of hydrochemical facies (pl. 2) shows that the predominant facies in the aquifer system is calcium bicarbonate. The hydrochemical facies of an aquifer system reflects its mineral composition, and the Edwards-Trinity aquifer system predominantly consists of carbonate rocks. However, at least seven other facies are present in the aquifer system.

Boxplots were constructed to show ranges of dissolved-solids concentrations associated with hydrochemical facies in water of the Edwards-Trinity aquifer system. Boxplots, as explained below, also show the median, interquartile range, quartile skew, and outlying values. All boxplots were constructed with a minimum of 25 chemical analyses.



Each hydrochemical facies has a distinct dissolved-solids range (fig. 5), which accounts for the generally similar patterns of the areal distributions of dissolved-solids concentrations and hydrochemical facies (pl. 2). The bicarbonate or mixed anion water is essentially fresh or marginally fresh, and the sulfate and chloride water for the most part is slightly saline. The evaporite minerals that commonly are the source of sulfate and chloride in water are highly soluble; thus, water associated with evaporite minerals tends to have higher dissolved-solids concentrations than water associated with carbonate minerals.

Edwards Aquifer in the Balcones Fault Zone

Water in the Edwards aquifer in the Balcones fault zone has the lowest median dissolved-solids concentration (297 mg/L, based on the 600 water samples) among the principal aquifers in the four geographic subareas. The variability in dissolved-solids concentrations, as indicated by an interquartile range of 93 mg/L, is also the lowest among the four subareas.

In the freshwater zone updip of the freshwater/saline-water transition zone, the water is almost exclusively calcium bicarbonate. In the transition zone it is more diverse, with seven facies represented; however, calcium sulfate is predominant in water from the transition zone. Almost all of the calcium bicarbonate analyses are from water in the freshwater zone and almost all of the calcium sulfate analyses are from water in the transition zone. Thus the boxplots in figure 6a essentially compare dissolved-solids concentrations of calcium bicarbonate water in the freshwater zone to calcium sulfate water in the transition zone. The calcium sulfate water has a median dissolved-solids concentration of 2,151 mg/L, more than 7 times higher than that of the calcium bicarbonate water (289 mg/L). Dissolved-solids concentrations also are substantially more variable in the calcium sulfate water.

The dissolved-solids concentrations and facies in water from the Balcones fault zone are consistent with the mineral composition of the rocks. This is indicated in the freshwater zone updip of the freshwater/saline-water transition zone, where the mineral composition is primarily calcite; in the more saline transition zone,

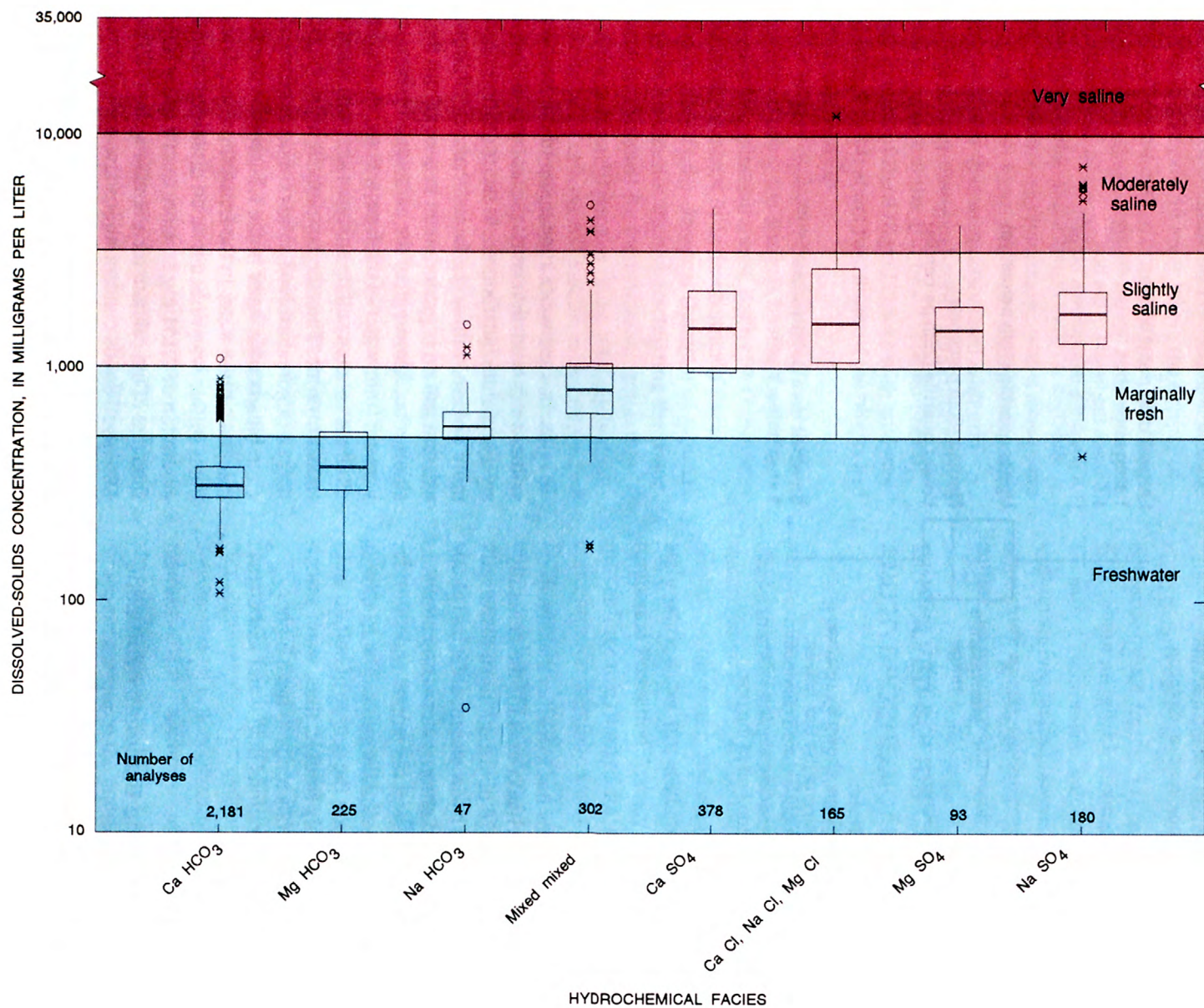


Figure 5. Ranges of dissolved-solids concentrations grouped by hydrochemical facies, Edwards-Trinity aquifer system.

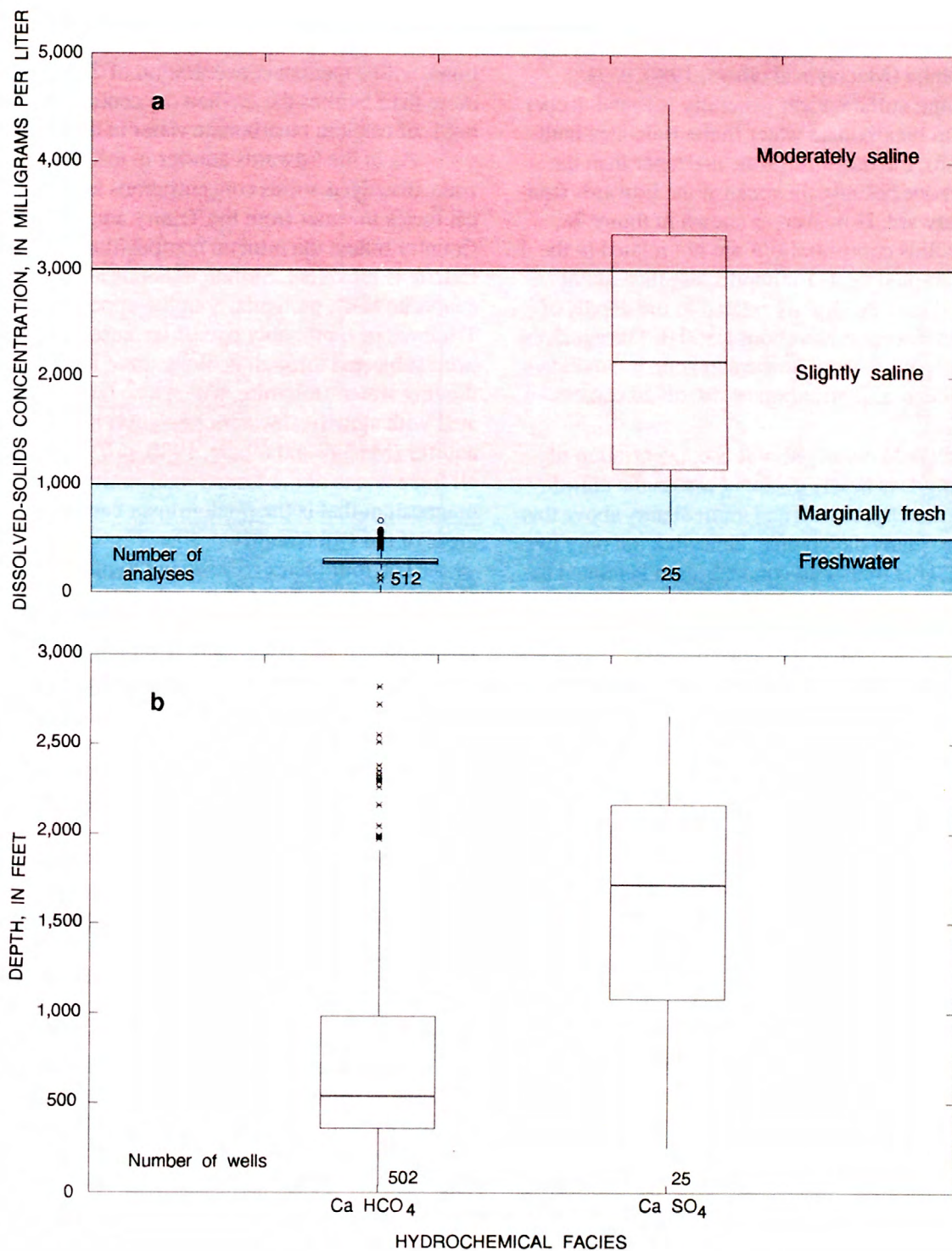


Figure 6. Ranges of (a) dissolved-solids concentrations grouped by hydrochemical facies, and (b) depths of sampled wells grouped by hydrochemical facies, Balcones fault zone.

calcite and dolomite are prevalent, but the rocks contain proportionately more gypsum, anhydrite, celestite, and strontianite (Maclay and others, 1980, p. 7).

Calcium sulfate water generally is found deeper than calcium bicarbonate water in the Balcones fault zone (fig. 6b); the transition zone is deeper than the freshwater zone because the rocks of the Edwards aquifer dip coastward. However, as shown in figure 7a, dissolved-solids concentrations are not related to the depths of sampled wells for depths less than about 1,500 ft, and may be slightly related to the depths of sampled wells deeper than about 1,500 ft. The aquifer's high transmissivity in the freshwater zone is conducive to a homogeneous distribution of dissolved constituents.

A threshold dissolved-solids concentration of about 225 mg/L is nearly constant across the entire range of depths (fig. 7a). At and immediately above this threshold are many data points; beneath it are only five data points. This threshold concentration is related to the fact that the major source of recharge to the Edwards aquifer is streamflow that originates as spring or base flow from carbonate rocks along the southern margin of the Edwards Plateau and in the interstream areas of the Hill Country. Having previously been in contact with carbonate rocks, the water entering the Edwards aquifer is a calcium bicarbonate water. According to Maclay and others (1980, p. 7), the recharge water is saturated with respect to calcite, except during storm periods when surface runoff is higher and associated dissolved-solids concentrations are correspondingly lower.

Trinity Aquifer in the Hill Country

Water in the Trinity aquifer in the Hill Country has higher dissolved-solids concentrations than water in the Edwards aquifer in the Balcones fault zone, and concentrations vary over a larger range. The median dissolved-solids concentration of the 532 Hill Country water samples is 537 mg/L and the interquartile range is 573 mg/L. The dissolved-solids map (pl. 2) shows areas of slightly saline water interspersed among areas of freshwater and marginally freshwater throughout the Hill Country.

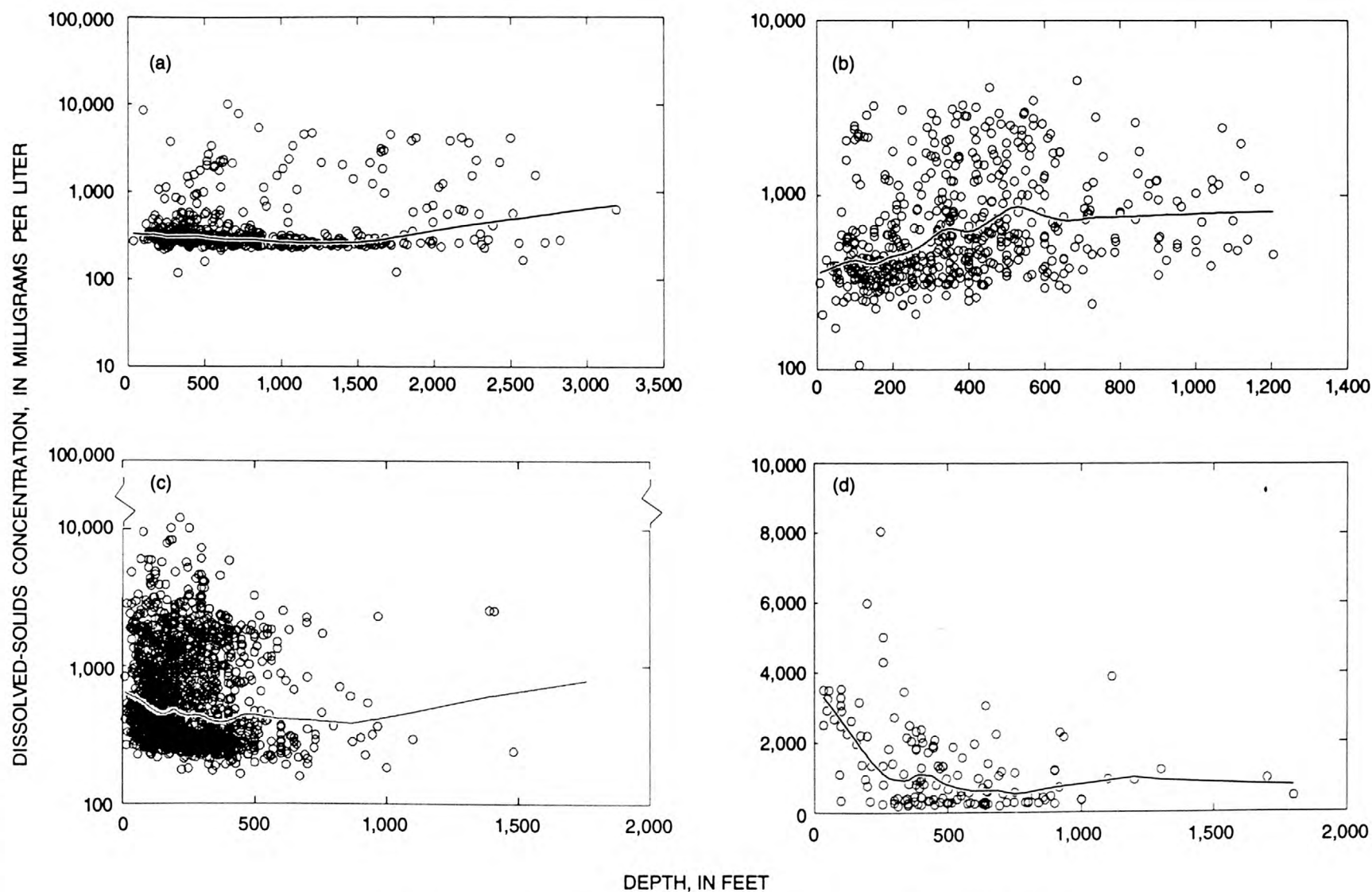
All eight hydrochemical facies are present in the Hill Country (pl. 2), but calcium bicarbonate is predominant. Boxplots of dissolved-solids concentrations associated with four facies (the facies represented in at

least 25 analyses each) (fig. 8a) show that calcium sulfate water has the highest dissolved-solids concentrations, with a median concentration of 2,119 mg/L—more than 5 times the median concentration of 381 mg/L of calcium bicarbonate water in the Hill Country.

As in the Edwards aquifer in the Balcones fault zone, dissolved-solids concentrations and hydrochemical facies in water from the Trinity aquifer in the Hill Country reflect the mineral composition of the rocks. Calcite is prevalent. Sulfate minerals associated with evaporite beds, particularly in the upper and lower Trinity zones, probably persist because they have not been subjected through geologic time to vigorously flowing water. Dolomite, which also tends to be associated with slow freshwater circulation in the Edwards aquifer (Maclay and others, 1980, p. 7), is common in all three zones of the Trinity aquifer. It contributes the magnesium that is the predominant cation in some areas of the Hill Country.

The four facies represented in most of the Hill Country analyses are distributed vertically throughout the saturated section (fig. 8b). However, calcium bicarbonate water commonly is found at shallower depths than magnesium bicarbonate, calcium sulfate, or magnesium sulfate waters. Dissolved-solids concentrations among all of the Hill Country water samples generally increase as the depths of sampled wells increase (fig. 7b) to a depth of about 520 ft, but show no relation beyond that depth.

The Trinity aquifer in the Hill Country is the most geologically and hydraulically stratified among the principal aquifers in the four subareas. Accordingly, boxplots of dissolved-solids concentrations from analyses associated with the upper, middle, and lower Trinity zones were made to indicate whether regional differences in concentrations exist among the zones (fig. 9). (For these boxplots, a subset of 363 Hill Country analyses, which excluded all analyses with multi-zone aquifer codes was selected.) The median dissolved-solids concentration of water samples is 583 mg/L for the upper Trinity, 510 mg/L for the middle Trinity, and 652 mg/L for the lower Trinity. The results of a multiple-stage Kruskal-Wallis test (Helsel and Hirsch, 1992, p. 200-202) on the three groups indicate that the median dissolved-solids concentration in water from the middle Trinity is different from that of the upper Trinity at an attained significance level of 0.068, and different from that of the lower Trinity at an attained significance level of 0.005. These results indicate that the dissolved-solids concentrations in water



Note: Fitted lines produced by LOWESS (LOcally WEighted Scatterplot Smoothing) procedure with smoothness factor (f) = 0.25 (Cleveland and McGill, 1984).

Figure 7. Dissolved-solids concentrations as a function of depth of sampled wells, (a) Balcones fault zone, (b) Hill Country, (c) Edwards Plateau, and (d) Trans-Pecos.

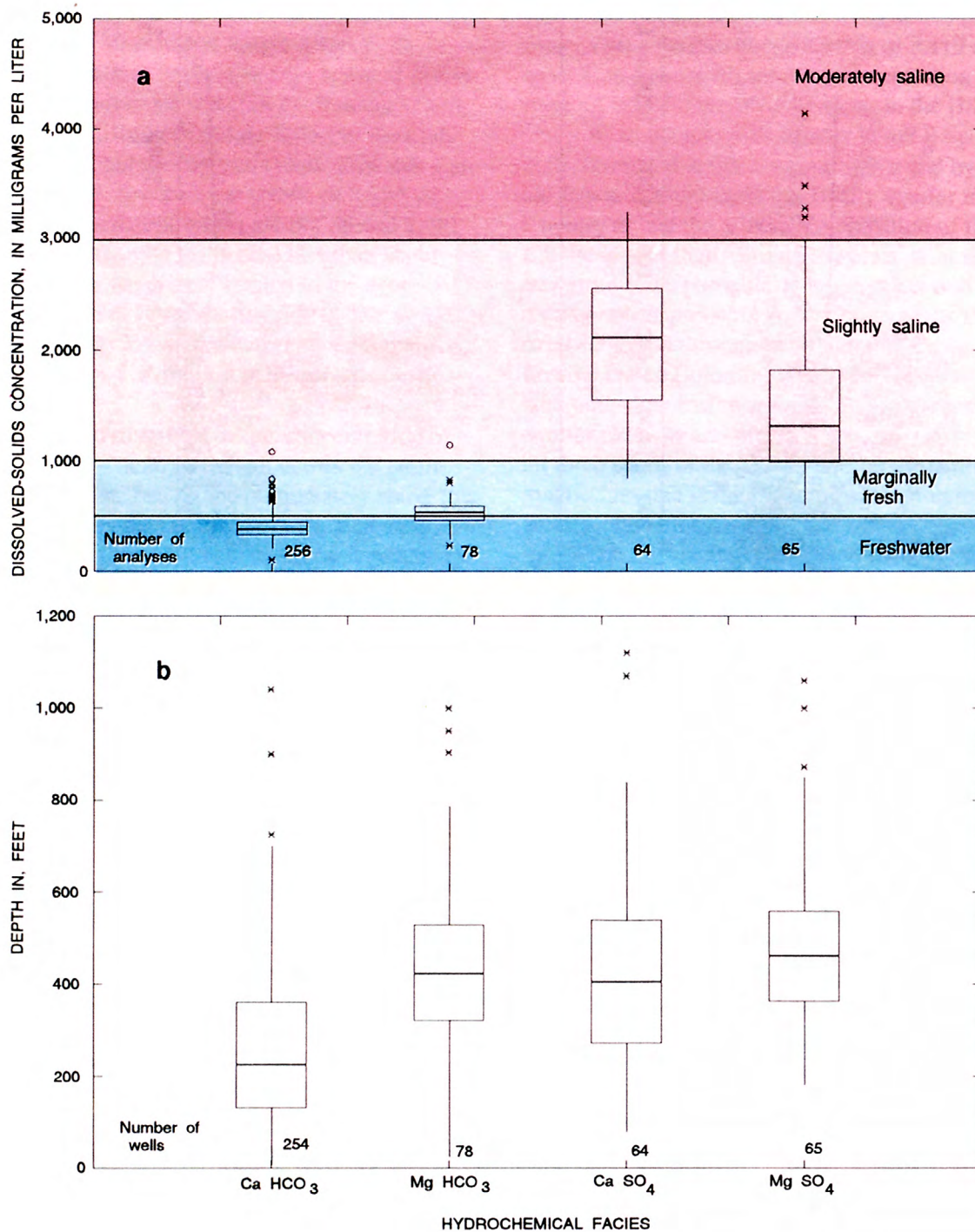


Figure 8. Ranges of (a) dissolved-solids concentrations grouped by hydrochemical facies, and (b) depths of sampled wells grouped by hydrochemical facies, Hill Country.

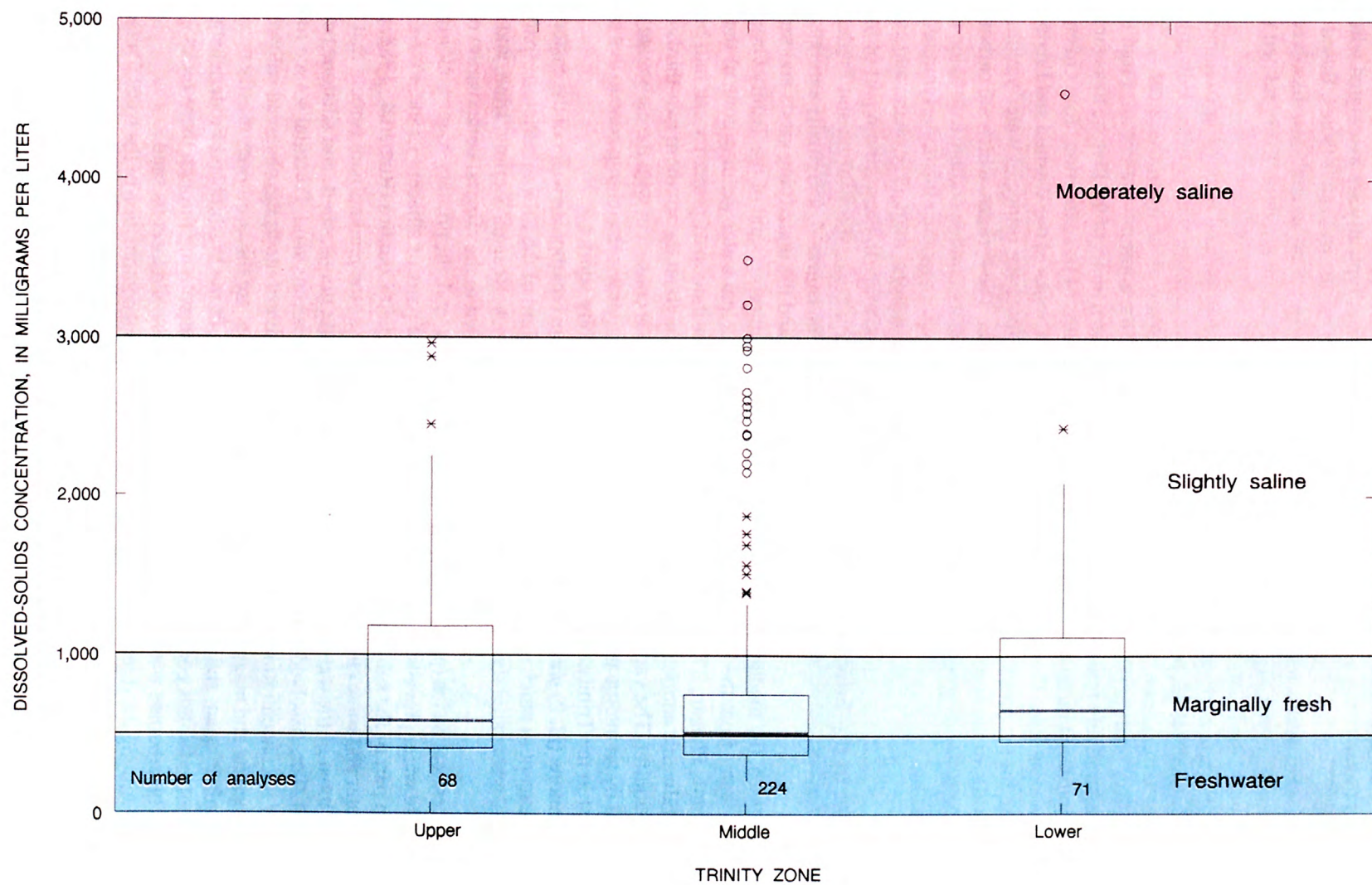


Figure 9. Ranges of dissolved-solids concentrations grouped by water-yielding zone of the Trinity aquifer, Hill Country.

from the middle Trinity zone are significantly different from those of the upper and lower Trinity zones, particularly the lower Trinity zone.

The results of the Kruskal-Wallis test also indicate that the dissolved-solids concentrations in water from the upper Trinity zone and the lower Trinity zone are not significantly different from each other. This result was unexpected. Ashworth (1983, p. 47) states that wells open to the upper Trinity zone "generally produce water of poor quality;" and (p. 60) that, because of the quality, comparatively few wells are completed in the upper Trinity, and those are exclusively for domestic and livestock use. The upper Trinity analyses in the data base for the present study may represent only the "best" wells in the zone, because wells yielding less desirable water may be abandoned, destroyed, or not reported.

Edwards-Trinity Aquifer in the Edwards Plateau

Based on 2,296 analyses, the median concentration of dissolved solids in water from the Edwards-Trinity aquifer in the Edwards Plateau, 379 mg/L, is higher than that from the Edwards aquifer, but lower than that from the Trinity aquifer. The variability in concentration, as indicated by an interquartile range of 547 mg/L, is similar to that in the Trinity. The map of dissolved-solids concentrations (pl. 2) shows fresh-water nearly everywhere except in much of the northwestern part of the subarea, where slightly saline water predominates.

The map of hydrochemical facies (pl. 2) shows a similar pattern; bicarbonate water prevails everywhere except in the northwestern part of the subarea, which contains mostly sulfate water and some chloride water. Seven facies characterize most of the waters of the Edwards Plateau (fig. 10a). The dissolved-solids concentrations and variability in concentration are nearly identical in calcium bicarbonate and magnesium bicarbonate water in the Edwards Plateau, and they are about the same as the dissolved-solids concentrations and variability of calcium bicarbonate water in the Balcones fault zone (fig. 6a). Among the three sulfate and one chloride facies in slightly saline water of the Edwards Plateau (fig. 10a), none has substantially greater dissolved-solids concentrations than the others.

The hydrochemical facies in the Edwards Plateau show no discernible relation to depths of sampled

wells (fig. 10b), although magnesium sulfate water and sodium sulfate water typically are associated with deeper wells than are the five other facies. Based on data from all Edwards Plateau analyses, dissolved-solids concentrations are not definitively related to depths of sampled wells (fig. 7c).

The hydrogeologic and mineralogic characteristics of the Edwards-Trinity aquifer in the Edwards Plateau account for some of the hydrochemical characteristics of the aquifer—but not all. From the southern and eastern limits of the Plateau to as far north as the southern parts of Reagan, Irion, Tom Green, and Concho Counties, rocks of the Washita and Fredericksburg Groups compose the principal water-yielding zone of the aquifer. These rocks, which are carbonates, are transmissive and saturated enough to provide ample water to wells without tapping the underlying sediments of sand, limestone, marl, clay, shale, and evaporite of the Trinity Group. In the northern part of the Plateau, the carbonates of the Washita and Fredericksburg Groups are unsaturated, marginally saturated, or locally missing, and the underlying sands and sandstones (basal Cretaceous sand of the Trinity Group) compose the principal water-yielding zone of the aquifer. Thus, the distribution of primarily calcium bicarbonate water throughout the southern two-thirds of the Edwards Plateau is consistent with the carbonate rocks composing the major water-yielding zone in that part of the Edwards-Trinity aquifer.

The calcium bicarbonate water of the eastern part of the northern third of the Edwards Plateau (parts of Howard, Glasscock, Reagan, Sterling, Irion, and Coke Counties) is related to the mineral composition of the basal Cretaceous sand, the primary water-yielding unit. A recent study of parts of adjacent Crane, Pecos, Upton, and Crockett Counties (Romanak, 1988, p. 27) identified calcite as the predominant cement that holds together the quartz grains, chert, and siltstone pebbles of the basal Cretaceous sand. Potential source rocks that also could contribute to the observed calcium bicarbonate facies are the overlying, mostly unsaturated carbonates of the Washita and Fredericksburg Groups. Water percolating through these rocks recharges the basal Cretaceous sand.

The mineral composition of the basal Cretaceous sand cannot account for the sulfate and chloride facies in the northwestern part of the Edwards Plateau. However, the following three potential sources of sulfate and chloride were considered: (1) the underlying Dockum aquifer or other adjacent Triassic rocks;

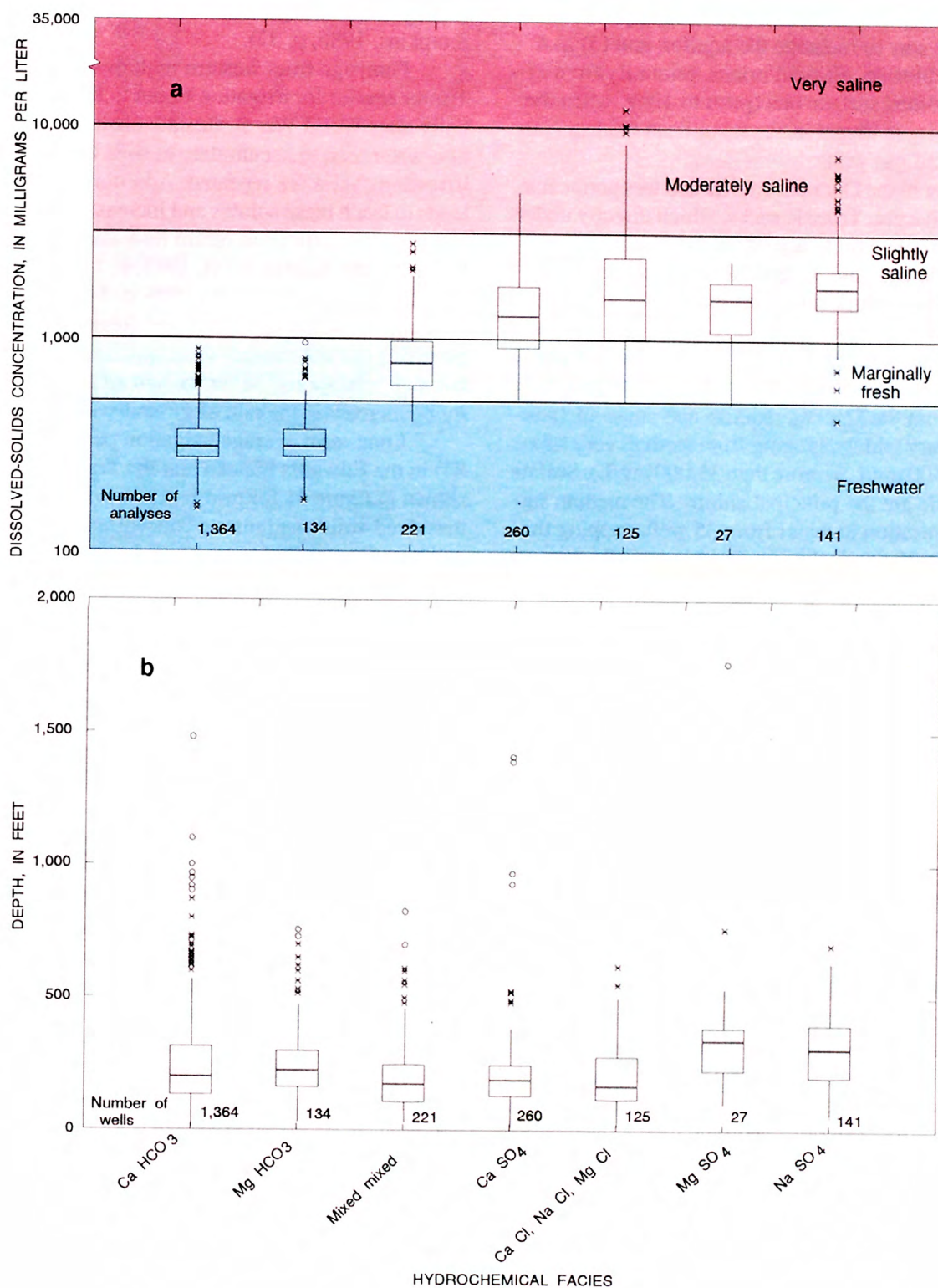


Figure 10. Ranges of (a) dissolved-solids concentrations grouped by hydrochemical facies, and (b) depths of sampled wells grouped by hydrochemical facies, Edwards Plateau.

(2) irrigation return flow that leaches accumulated solutes from irrigated areas as it passes through the soil zone on its way to recharge the aquifer; and (3) as a source of chloride, oil-field brines, primarily from disposal in unlined surface pits (prior to 1969, when the practice became illegal in Texas) or from inadequately cased oil and gas wells.

Water in the Dockum aquifer and less permeable, laterally adjacent, Triassic rocks, which directly underlie the Edwards-Trinity aquifer in the northwestern Edwards Plateau (fig. 3), generally has higher dissolved-solids concentrations than water in the Edwards-Trinity aquifer. On the basis of 111 analyses from the water-quality data base of the Texas Water Development Board, dissolved-solids concentrations in water from the Dockum aquifer and adjacent Triassic rocks vary widely, ranging from fresh to very saline (less than 500 mg/L to more than 35,000 mg/L). Sulfate and chloride are the principal anions. The median sulfate concentration in water from 35 wells tapping the Dockum aquifer and adjacent Triassic rocks in the area of predominantly sulfate facies in the northwestern part of the Plateau is 1,568 mg/L. The median chloride concentration in water from the same analyses is 912 mg/L. The hydrochemical characteristics of these units and their proximity to the Edwards-Trinity aquifer in the northwestern Edwards Plateau make these units a likely source of sulfate and chloride in water of the Edwards-Trinity aquifer. However, comparison of hydraulic heads from about 30 wells open to the Dockum aquifer and adjacent rocks of Triassic age with a regional potentiometric-surface map of the Edwards-Trinity aquifer for winter 1974-75 (Kuniansky, 1990) shows that heads in the Dockum aquifer and adjacent Triassic rocks were mostly about equal to or below heads in the Edwards-Trinity aquifer. A regional upward gradient from the Dockum aquifer and adjacent Triassic rocks to the Edwards-Trinity aquifer is not evident. Therefore, the underlying Triassic units probably are not a principal modern-day source of the sulfate and chloride. During previous geologic time, however, a regional upward gradient may have existed. According to Dutton and Simpkins (1986, p. 26), before the formation of the Pecos River valley (which began during the Tertiary Period), the Triassic rocks may have been hydraulically connected to recharge areas to the west at altitudes above 6,000 ft, causing heads that were considerably higher than current heads. A major source of sulfate and chloride in water from the Triassic units is evaporites from late Permian rocks that began to be

removed by dissolution late in the Tertiary Period (Maley and Huffington, 1953, p. 541; Dutton and Simpkins, 1986, p. 32).

Pumpage from western regions of the Edwards-Trinity aquifer for irrigation began to increase substantially after World War II. Residual solutes from irrigation water tend to accumulate in soils as annual irrigation cycles are repeated. Additional irrigation tends to leach these solutes and increases the dissolved-solids concentrations in return flow that ultimately recharges the aquifer (Hem, 1985, p. 117). According to Ashworth and Christian (1989, p. 34), irrigation pumpage in Midland, Upton, and Reagan Counties generally has not caused water-quality deterioration, but may be responsible for the spread of existing salinity by increasing the rate of ground-water movement.

Long-term average irrigation pumpage (1958-84) in the Edwards Plateau and the Trans-Pecos is shown in figure 11 for grid blocks having data on dissolved-solids and nitrate concentrations. Dissolved-solids concentrations were plotted against the respective long-term average irrigation pumpage (fig. 12a) to indicate whether regional ground-water chemistry is related to irrigation pumpage. [The magnitude and distribution of irrigation pumpage are from a data base prepared for computer simulation of flow in the Edwards-Trinity aquifer system (Kuniansky and Holligan, 1994, fig. 6).] If irrigation return flow that is more saline than natural ground water has affected regional water quality in the Edwards-Trinity aquifer, then dissolved-solids concentrations probably would be greater in areas of greater pumpage for irrigation; that is, a monotonic relation would exist between the two variables. The graph in figure 12a does not show a strong monotonic relation between dissolved-solids concentration and pumpage. The rank correlation coefficient between dissolved-solids concentration and pumpage is 0.333. The rank correlation coefficient is a measure of the strength of a monotonic relation. Values range between +1 and -1; the strength of the relation increases as the value approaches +1 or -1.

Another possible indicator that irrigation has affected regional ground-water chemistry is nitrate concentrations. Leached nitrogen from fertilizers applied to irrigated crops has the potential to increase nitrate concentrations in ground water (Hem, 1985, p. 125). Nitrate concentrations were plotted as a function of long-term average irrigation pumpage (fig. 12b). The plot shows little relation between nitrate concentrations and the magnitude of irrigation pumpage from

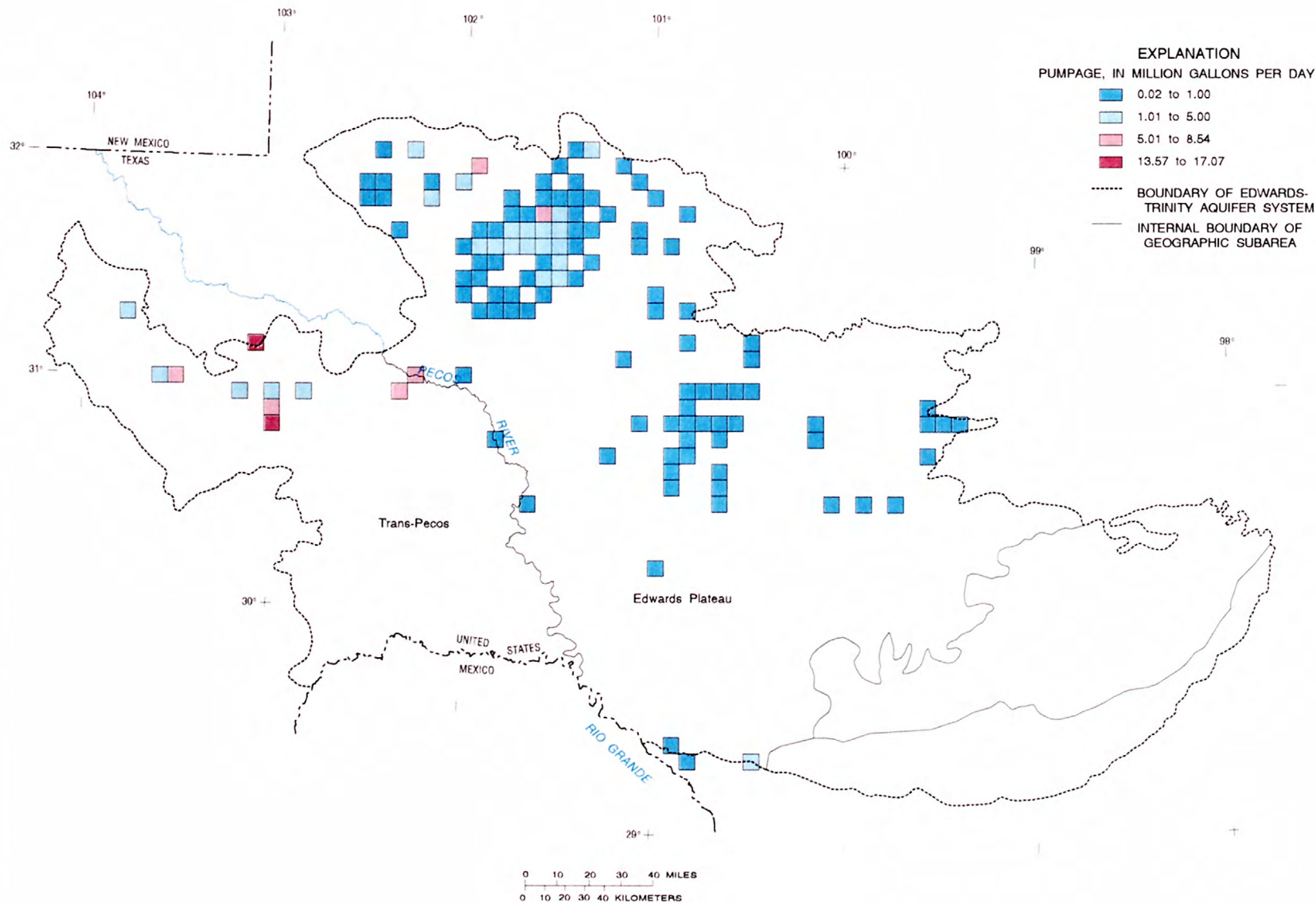
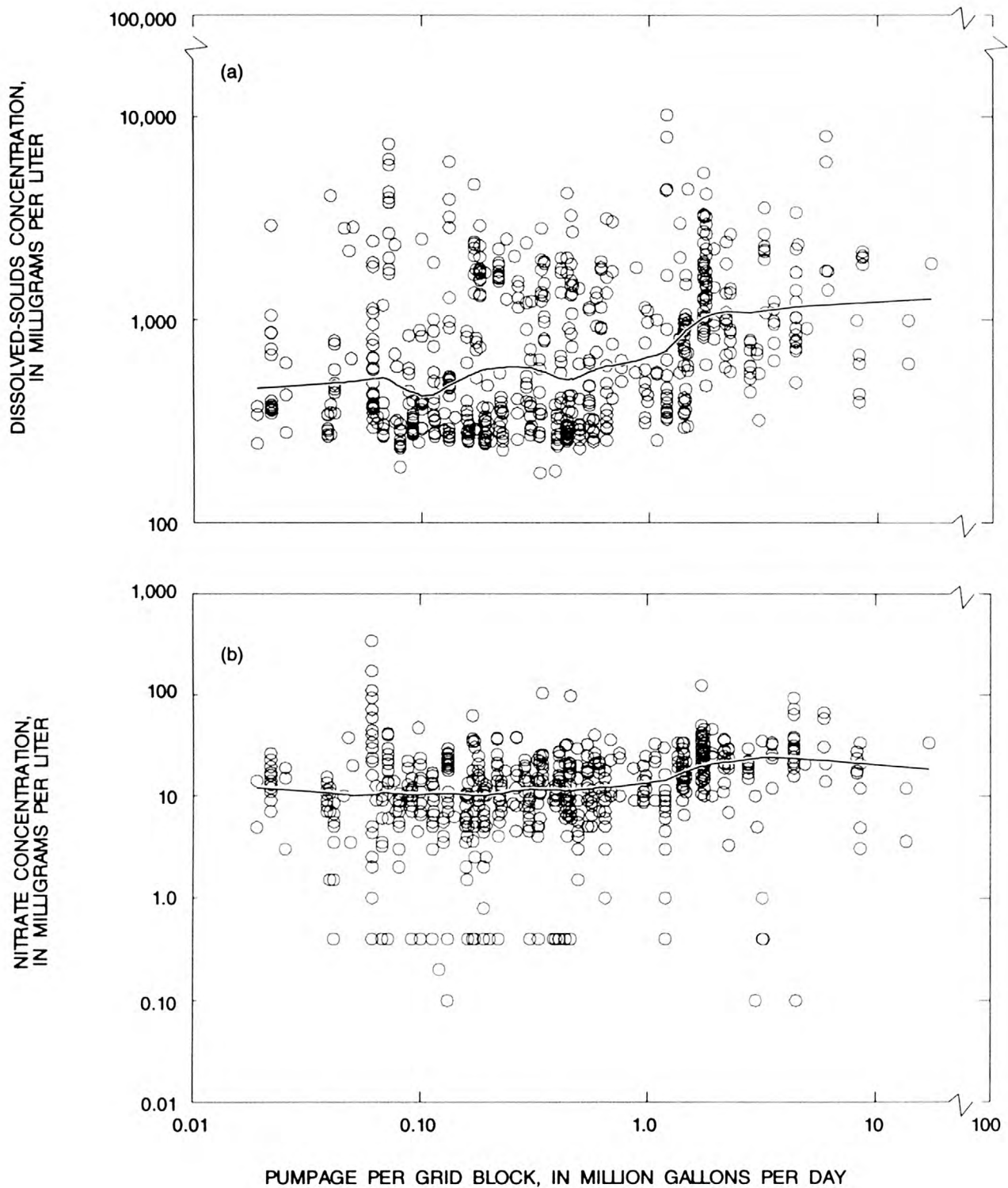


Figure 11. Long-term average irrigation pumpage in grid blocks having data on dissolved-solids and nitrate concentrations, Edwards Plateau and Trans-Pecos.



Note: Fitted lines produced by LOWESS (LOcally WEighted Scatterplot Smoothing) procedure with smoothness factor (f) = 0.25 (Cleveland and McGill, 1984).

Figure 12. (a) Dissolved-solids concentrations as a function of long-term average irrigation pumpage, and (b) nitrate concentrations as a function of long-term average irrigation pumpage, Edwards Plateau and Trans-Pecos.

the Edwards-Trinity aquifer. The rank correlation coefficient between nitrate concentrations and pumpage is 0.318.

Drilling for oil and gas in the northwestern part of the Edwards Plateau began in the early part of the 20th century. Brines produced in the process and disposed into unlined surface pits before the practice became illegal in 1969 probably leaked downward to the ground-water system (Ashworth and Christian, 1989, p. 32). Brines in the southern High Plains of Texas (adjacent to the project area) exhibit sodium chloride facies and very high equivalent ratios of chloride to sulfate (ranging from 17 to 170) (Nativ and Gutierrez, 1988, p. 21). Individual water wells in Upton and Reagan Counties have been affected by water from nearby brine-disposal pits (White, 1968, p. 41; Walker, 1979, p. 100). Underground disposal of brines associated with oil and gas production or secondary oil and gas recovery operations can increase subsurface pressure, causing saline water to rise in old, corroded casings and to leak into freshwater zones (Ashworth, 1990, p. 31). However, regional changes in ground-water chemistry associated with oil and gas production have not been documented.

The number of pre-1970 oil and gas wells in the Edwards Plateau and the Trans-Pecos is shown in figure 13 for grid blocks having data on dissolved-solids and chloride concentrations. Dissolved-solids concentrations were plotted against the number of oil and gas wells constructed before 1970 (fig. 14a) to indicate whether regional ground-water chemistry is related to oil and gas production. Data on the number and distribution of pre-1970 oil and gas wells are from Petroleum Information Corporation (Denver, Colo.), which maintains a data base of all known oil and gas wells in Texas and other states. If brines associated with oil and gas production have affected regional ground-water chemistry, then dissolved-solids and chloride concentrations probably would be greater in areas with a greater number of pre-1970 oil and gas wells; monotonic relations would exist between the variables. The graphs in figure 14 show no definable relation between dissolved-solids concentration and the number of oil and gas wells, or between chloride concentration and the number of oil and gas wells. The rank correlation coefficient between dissolved-solids concentration and the number of oil and gas wells is 0.363, and between chloride concentration and the number of oil and gas wells is 0.341.

Edwards-Trinity Aquifer in the Trans-Pecos

The median concentration of dissolved solids among the 143 water samples from the Edwards-Trinity aquifer in the Trans-Pecos is 929 mg/L, about 2-1/2 times higher than that in the Edwards Plateau and the highest median concentration among the four subareas. The variability in concentration, as indicated by an interquartile range of 1,626 mg/L, is about 3 times higher than that in water from the aquifer in the Edwards Plateau and the highest among the subareas. The map of dissolved-solids concentrations (pl. 2) shows fresher water in the southeastern part of the Trans-Pecos, the region known as the Stockton Plateau, than in the northwestern part, the region coincident with the southern part of the Toyah basin (fig. 4). Almost all of the saline water in the Trans-Pecos is in the Toyah basin.

As in the other three subareas, the areal distribution of hydrochemical facies in the Trans-Pecos is related to the distribution of dissolved-solids concentrations. Fresh, calcium bicarbonate water predominates in the Stockton Plateau, and the more saline mixed and calcium sulfate facies are more common in the Toyah basin. The contrast in dissolved-solids concentrations among those three facies is shown in figure 15a. The median dissolved-solids concentrations in calcium bicarbonate water (294 mg/L) and calcium sulfate water (2,156 mg/L) are virtually identical to those in calcium bicarbonate water and calcium sulfate water in the freshwater and transition-zone parts, respectively, of the Balcones fault zone (fig. 6a).

Unlike water in the Balcones fault zone, calcium bicarbonate water in the Trans-Pecos typically is deeper than calcium sulfate water. The median depth of sampled wells yielding calcium bicarbonate water is 534 ft, whereas the median depth of sampled wells yielding calcium sulfate water is 400 ft (fig. 15b). Wells yielding calcium bicarbonate water are deeper because the depth to water in the Stockton Plateau, where calcium bicarbonate water predominates, generally is greater than in the Toyah basin, where calcium sulfate water predominates. The median depth among the sampled wells in the Stockton Plateau is 585 ft, whereas the median depth among the sampled wells in the Toyah basin is 381 ft.

Dissolved-solids concentrations decrease as depth increases in wells that are less than about 300 ft deep in the Trans-Pecos (fig. 7d). Thirty-one of the 33 sampled wells less than 300 ft deep are in the Toyah

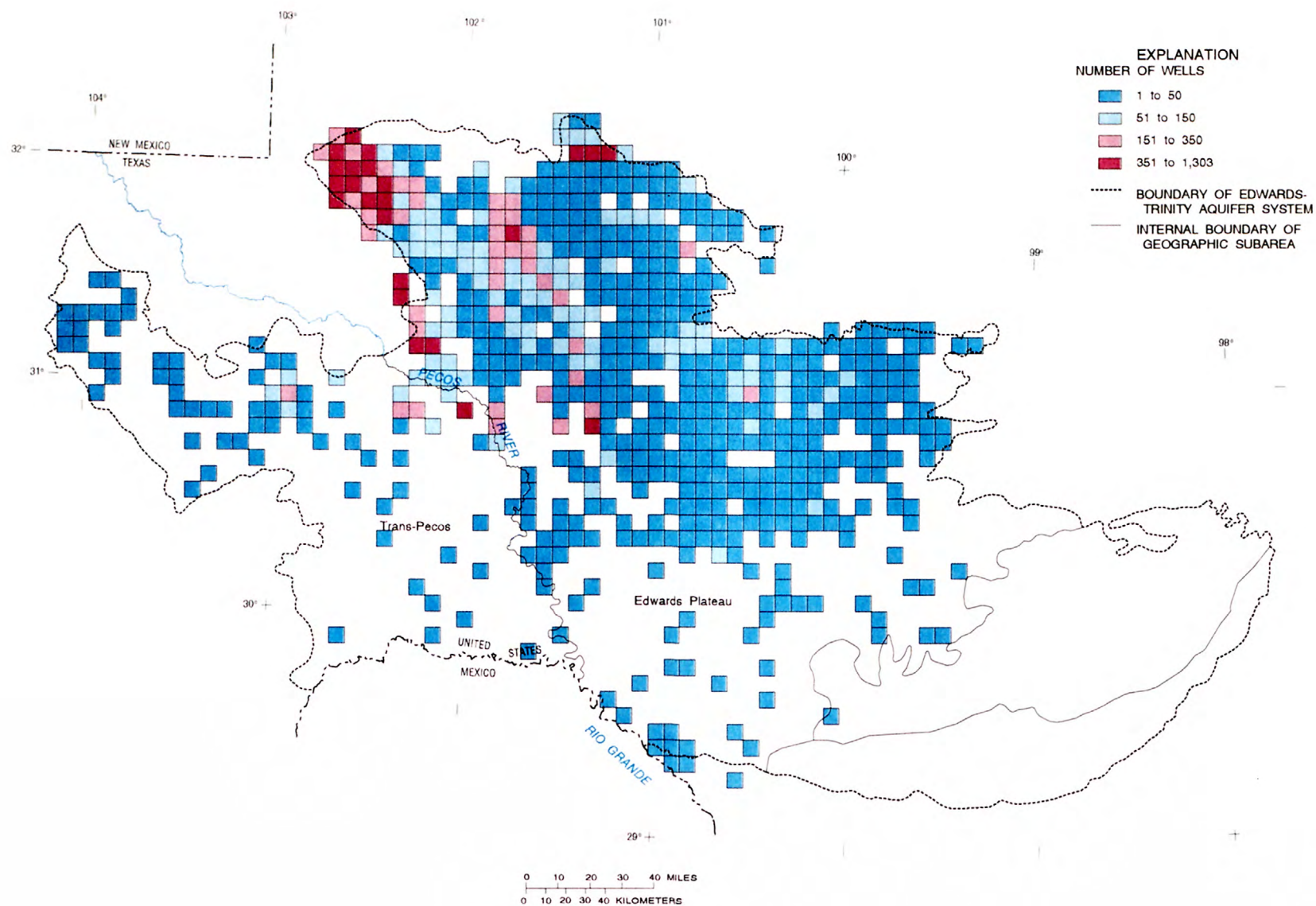
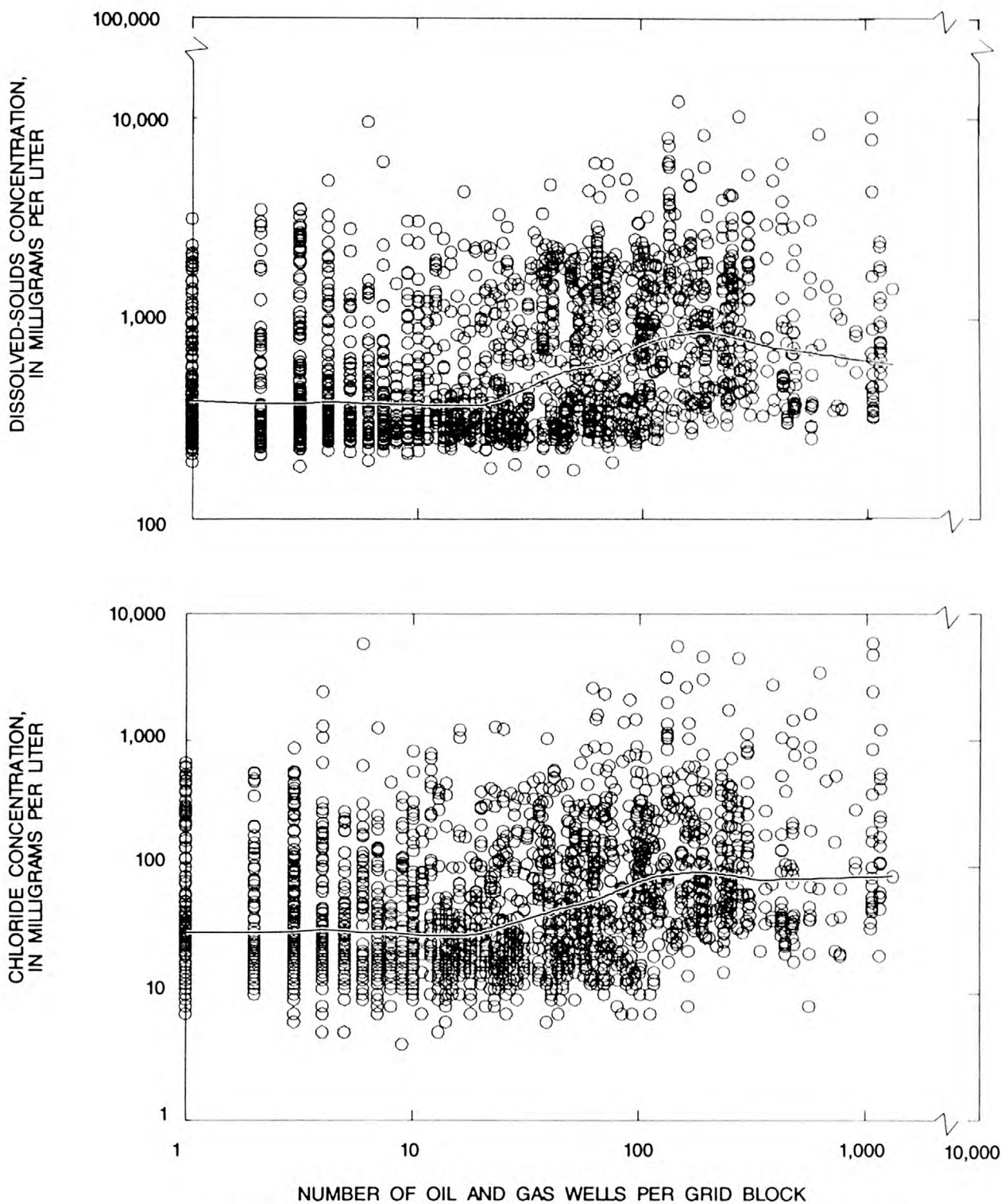


Figure 13. Number of pre-1970 oil and gas wells in grid blocks having data on dissolved-solids and chloride concentrations, Edwards Plateau and Trans-Pecos.



Note: Fitted lines produced by LOWESS (LOcally WEighted Scatterplot Smoothing) procedure with smoothness factor (f) = 0.25 (Cleveland and McGill, 1984).

Figure 14. (a) Dissolved-solids concentrations as a function of number of pre-1970 oil and gas wells, and (b) chloride concentrations as a function of number of pre-1970 oil and gas wells, Edwards Plateau and Trans-Pecos.

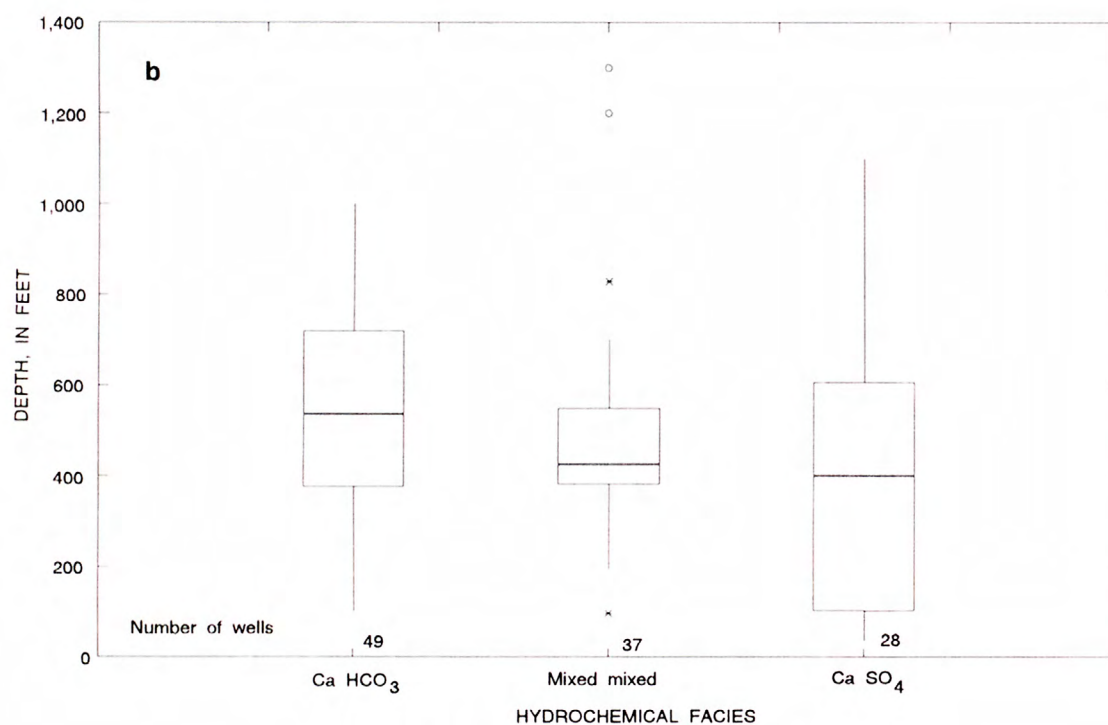
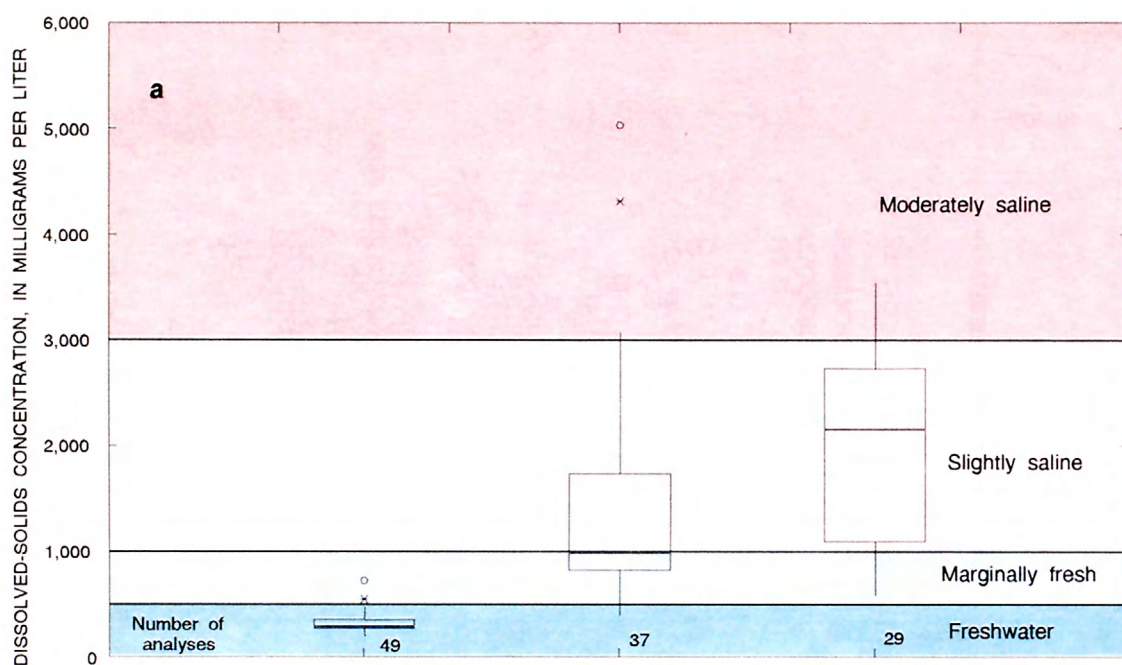


Figure 15. Ranges of (a) dissolved-solids concentrations grouped by hydrochemical facies, and (b) depths of sampled wells grouped by hydrochemical facies, Trans-Pecos.

basin. A relation between dissolved-solids concentration and depth is not apparent among sampled wells deeper than about 300 ft.

In the Stockton Plateau, the principal water-yielding zone probably is the lower part of the aquifer, the basal Cretaceous sand. The predominantly carbonate rocks of the Washita and Fredericksburg Groups that form the upper part of the aquifer are less permeable, or they lie above the water table. As in the eastern part of the northern third of the Edwards Plateau, the calcium and bicarbonate ions are associated with calcite within the basal Cretaceous sand (or in the Glen Rose Limestone, which is in some southern parts of the aquifer); or with recharge from the overlying, mostly unsaturated, Washita and Fredericksburg Groups.

Sources of sulfate or chloride within rocks forming the Edwards-Trinity aquifer in the Toyah basin are not known. However, other possible sources include adjacent aquifers, irrigation return flow, and oil-field brines.

Adjacent hydraulically connected aquifers are probable sources of the sulfate and chloride facies characterizing much of the water in the Toyah basin. In the parts of the Toyah basin where the Edwards-Trinity aquifer is directly overlain by the Cenozoic Pecos alluvium aquifer (fig. 2), the two aquifers are hydraulically connected and form a continuous water-yielding unit. Water in the Cenozoic Pecos alluvium aquifer is fresh to moderately saline. Gypsum is a component of the Cenozoic Pecos alluvium and thus may be a source of sulfate in water of the Edwards-Trinity aquifer.

Directly underlying the Edwards-Trinity aquifer in the Toyah basin are rocks of Triassic and Permian age that, in places, form the Dockum aquifer and the Rustler aquifer, respectively (fig. 3). Triassic and Permian red beds lie between the Edwards-Trinity and the Rustler aquifers (and adjacent to the Dockum aquifer) in much of the area. Water in the Rustler aquifer, the most areally extensive underlying unit, is slightly to very saline and generally has higher dissolved-solids concentrations than water in the Edwards-Trinity aquifer. Anhydrite is a major component of the Rustler Formation, which probably accounts for the typically high concentrations of sulfate relative to other anions in water from the Rustler aquifer. The degree of vertical hydraulic connection across the red beds between the Rustler and the Edwards-Trinity aquifers is not well documented. Hydraulic heads in several wells open to the Rustler aquifer in southern Reeves County in recent years were about the same as vertically adjacent heads

in the Edwards-Trinity aquifer during winter 1974-75 (Kuniansky, 1990). Ground-water development has lowered heads in the Rustler aquifer in west-central Pecos County (Armstrong and McMillion, 1961, p. 35); however, heads in two wells open to the Rustler aquifer in that area in 1987 were about 40 ft higher than heads in nearby wells open to the Edwards-Trinity aquifer (T.A. Small, U.S. Geological Survey, written commun., 1989).

Sharp (1989, p. 129) states that the sulfate facies characteristic of the western and northwestern parts of the Toyah basin indicate that the water originates in the Rustler Hills (fig. 3), the outcrop area of the Rustler aquifer and other rocks of the Ochoan series (pl. 1) in eastern Culberson County. Whether this water recharges the Toyah basin by subsurface flow or by infiltration along draws draining eastward from the Rustler Hills is unknown.

Another hydrogeologic unit that potentially contributes saline water to the Edwards-Trinity aquifer is the western segment of the Capitan aquifer (fig. 3). (The eastern segment of the Capitan aquifer, in Pecos County, is deeply buried and hydraulically isolated from the Edwards-Trinity aquifer.) LaFave and Sharp (1987) hypothesize that the Capitan aquifer is the origin of part of the discharge issuing from springs in southern Reeves County. They base their interpretation on regional geology and the "striking" geochemical similarity between the water of the Capitan aquifer and the springs; water from both is dominated by chloride and sulfate anions.

Irrigation pumpage is widespread in the Toyah basin and accounts for most of the water use there. Ashworth (1990, p. 31-32) reports that, in Reeves County, "significant" increases in dissolved solids have occurred in water samples from some wells (presumably resulting from irrigation return flow), but water-quality deterioration is recognized in only a few wells and generally has not affected the entire irrigation area. Ashworth (1990, p. 32) further states that water-quality deterioration resulting from irrigation return flow would have a more pronounced effect on the upper part of the aquifer. If this is so, then the relation of decreasing dissolved solids with depth (fig. 7d) may indicate the effect of irrigation return flow. Although the previously discussed graphs of dissolved-solids concentration and nitrate concentration as a function of long-term irrigation pumpage (fig. 12) showed no association between concentrations of these constituents and

the magnitude of pumpage, little of that data refers to the Trans-Pecos (fig. 11).

Brine disposal in unlined pits prior to 1970 probably occurred in the Trans-Pecos, although the density of oil and gas wells is low compared to that in the northwestern part of the Edwards Plateau (fig. 13). The density of pre-1970 oil and gas wells does not show clear associations with either dissolved-solids or chloride concentrations in water from the Edwards-Trinity aquifer (fig. 14).

SUMMARY

The Edwards-Trinity aquifer system is a sequence of near-surface, hydraulically connected, carbonate and quartzose clastic rocks of Cretaceous age that underlies about 42,000 mi² of west-central Texas. The aquifer system comprises three aquifers and two confining units. The aquifers are the Edwards, the Trinity, and the Edwards-Trinity. These aquifers are laterally adjacent except in the southeastern part of the area, where the coastward dip of the units steepens and part of the Trinity aquifer extends beneath the Edwards aquifer. The confining units of the system are the Navarro-Del Rio, which directly overlies the downdip part of the Edwards aquifer, and the Hammett, which is within the Trinity aquifer updip of the Edwards aquifer and within the southeastern part of the Edwards-Trinity aquifer. The coastward extent of freshwater flow in the aquifer system is limited by a freshwater/saline-water transition zone of slightly to moderately saline water.

For description, the aquifer system is divided into four geographic subareas—the Balcones fault zone, the Hill Country, the Edwards Plateau, and the Trans-Pecos. The Balcones fault zone is defined in this report as being coincident with the area where the Edwards is the principal aquifer. The Hill Country coincides with the area where the Trinity is the principal aquifer. Although the Trinity exists beneath the Edwards in the Balcones fault zone, it is not the principal aquifer there. The Edwards Plateau and the Trans-Pecos together are coincident with the area of the Edwards-Trinity aquifer.

The lithology of the principal aquifers in each of the four geographic subareas varies but is mostly carbonate rock, except in the lower part of the Edwards-Trinity aquifer, where sand and sandstone predominate. The Trinity aquifer in the Hill Country is the most geologically and hydraulically stratified among the principal aquifers in the four subareas. It commonly is

divided into three water-yielding zones—the upper Trinity, the middle Trinity, and the lower Trinity.

Maps of dissolved-solids concentrations and hydrochemical facies were made from a data base of 3,571 analyses of water samples from 3,571 wells. Six hundred water samples are from the Balcones Fault zone and the adjacent freshwater/saline-water transition zone, 532 are from the Hill Country, 2,296 are from the Edwards Plateau and the adjacent freshwater/saline-water transition zone, and 143 are from the Trans-Pecos. The median year of sample collection is 1969; about one-half of the samples were collected from 1966 through 1975.

A major part of the Edwards-Trinity aquifer system contains freshwater, but sizable parts contain marginally fresh or slightly saline water. The predominant hydrochemical facies in the aquifer system is calcium bicarbonate; but, at least seven other facies are present in the aquifer system. Each facies has a distinct dissolved-solids range, which accounts for generally similar patterns in the areal distributions of dissolved-solids concentrations and hydrochemical facies.

Water in the Edwards aquifer in the Balcones fault zone has the lowest dissolved-solids concentrations among the principal aquifers in the four geographic subareas. The median dissolved-solids concentration of 600 water samples from the Balcones fault zone is 297 mg/L. The variability in dissolved-solids concentration, as indicated by an interquartile range of 93 mg/L, is also the lowest among the four subareas.

The hydrochemical facies in the Balcones fault zone are consistent with the mineral composition of the rocks. In the freshwater zone updip of the freshwater/saline-water transition zone, the mineral composition is primarily calcite and the water is almost exclusively calcium bicarbonate. In the mostly slightly saline water of the transition zone, calcite and dolomite are prevalent, but the rocks contain proportionately more sulfate minerals; calcium sulfate predominates among the analyses from the transition zone.

Water in the Trinity aquifer in the Hill Country has considerably higher dissolved-solids concentrations than water in the Edwards aquifer in the Balcones fault zone, and the concentrations vary over a larger range. The median dissolved-solids concentration of 532 Hill Country water samples is 537 mg/L and the interquartile range is 573 mg/L. Areas of slightly saline water are interspersed among areas of freshwater and marginally freshwater throughout the Hill Country.

The distribution of hydrochemical facies varies in the Hill Country. Four bicarbonate and sulfate facies, distributed vertically throughout the saturated section, are represented in most of the Hill Country analyses; calcium bicarbonate predominates. As in the Edwards aquifer in the Balcones fault zone, hydrochemical facies in water from the Trinity aquifer in the Hill Country reflect the mineral composition of the rocks. Calcite is prevalent, but sulfate minerals associated with evaporite beds are common, particularly in the upper and lower Trinity zones.

The median dissolved-solids concentration of water samples is 583 mg/L for the upper Trinity, 510 mg/L for the middle Trinity, and 652 mg/L for the lower Trinity. The dissolved-solids concentrations in water from the middle Trinity zone are significantly different from those of the other two zones.

The median dissolved-solids concentration of 2,296 water samples in the Edwards-Trinity aquifer in the Edwards Plateau, 379 mg/L, is higher than that in the Edwards aquifer, but lower than that in the Trinity aquifer. The variability in concentration, as indicated by an interquartile range of 547 mg/L, is similar to that in the Trinity. Freshwater is nearly everywhere except in much of the northwestern part of the subarea, where slightly saline water predominates.

Hydrochemical facies are distributed in a pattern similar to dissolved-solids concentrations. Bicarbonate water prevails everywhere except in the northwestern part of the subarea, which contains mostly sulfate water and some chloride water. The hydrogeologic and mineralogic characteristics of the Edwards-Trinity aquifer in the Edwards Plateau account for some of the hydrochemical characteristics of the aquifer—but not all. The calcium bicarbonate water in the southern two-thirds of the Edwards Plateau is consistent with the carbonate rocks composing the major water-yielding zone in that part of the Edwards-Trinity aquifer. The calcium bicarbonate water of the eastern part of the northern third of the Edwards Plateau is related to calcite in the sandy basal unit of the aquifer, which is most of the saturated part of the aquifer, or to recharge that passes through the overlying, mostly unsaturated carbonate rocks of the upper part of the aquifer.

The mineral composition of the basal Cretaceous sand cannot account for the sulfate and chloride facies of the northwestern part of the Edwards Plateau. However, the following three potential sources were considered: (1) the underlying Dockum aquifer or other Triassic rocks; (2) irrigation return flow; and (3) as a

source of chloride, oil-field brines. The proximity to the Edwards-Trinity aquifer and the chemical characteristics of the Dockum aquifer and other Triassic rocks, together with hypothesized geologic history of the area, make that source the most probable. Attempts to relate dissolved-solids and nitrate concentrations to the magnitude of irrigation pumpage resulted in no monotonic relation between the variables. Similarly, attempts to relate dissolved-solids and chloride concentrations, respectively, to the number of oil and gas wells resulted in no monotonic relation between the variables.

The median concentration of dissolved solids among the 143 water samples from the Edwards-Trinity aquifer in the Trans-Pecos is 929 mg/L, about 2-1/2 times higher than that in the aquifer in the Edwards Plateau and the highest median concentration among the four subareas. The variability in concentration, as indicated by an interquartile range of 1,626 mg/L, is about 3 times higher than that in water from the aquifer in the Edwards Plateau and the highest among the subareas. Fresher water is in the southeastern part of the Trans-Pecos, a region known as the Stockton Plateau, than in the northwestern part, a region coincident with the southern part of the Toyah basin. Almost all of the saline water in the Trans-Pecos is in the Toyah basin.

As in the other three subareas, the distribution of hydrochemical facies in the Trans-Pecos is related to the distribution of dissolved-solids concentrations. Fresh, calcium bicarbonate water predominates in the Stockton Plateau, and mixed and calcium sulfate facies are more common in the Toyah basin. In the Stockton Plateau, as in the eastern part of the northern third of the Edwards Plateau, the calcium bicarbonate ions are associated with calcite in the sandy basal unit of the aquifer; or with recharge through the overlying, mostly unsaturated carbonate rocks forming the upper part of the aquifer.

Sources of sulfate or chloride within rocks forming the Edwards-Trinity aquifer in the Toyah basin are not known. However, other sources external to the aquifer are possible. These sources include hydraulically connected aquifers, irrigation return flow, and oil-field brines. Adjacent, hydraulically connected aquifers—the overlying Cenozoic Pecos alluvium, the underlying Dockum, Rustler, and Capitan—are the probable source of the sulfate and chloride facies characterizing much of the water in the Edwards-Trinity aquifer in the Toyah basin.

REFERENCES

- Armstrong, C.A., and McMillion, L.G., 1961, Geology and ground-water resources of Pecos County, Texas: Texas Board of Water Engineers Bulletin 6106, v. I, 241 p.
- Ashworth, J.B., 1983, Ground-water availability of the Lower Cretaceous formations in the Hill Country of south-central Texas: Texas Department of Water Resources Report 273, 174 p.
- 1990, Evaluation of ground-water resources in parts of Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas: Texas Water Development Board Report 317, 51 p.
- Ashworth, J.B., and Christian, P.C., 1989, Evaluation of ground-water resources in parts of Midland, Reagan, and Upton Counties, Texas: Texas Water Development Board Report 312, 52 p.
- Ashworth, J.B., and Flores, R.R., 1991, Delineation criteria for the major and minor aquifer maps of Texas: Texas Water Development Board LP-212, 27 p.
- Back, William, 1960, Origin of hydrochemical facies of ground water in the Atlantic Coastal plain: International Geological Congress, 21st, Copenhagen, 1960 [Proceedings], pt. 1, p. 87-95.
- 1961, Techniques for mapping of hydrochemical facies, in *Short papers in the geologic and hydrologic sciences*, articles 293-435, Geological Survey Research 1961: U.S. Geological Survey Professional Paper 424-D, p. D380-D382.
- Barker, R.A., Bush, P.W., and Baker, E.T., Jr., 1994, Geologic and hydrogeologic setting of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Water-Resources Investigations Report 94-4039, 50 p.
- Brand, J.P., and Deford, R.K., 1958, Comanchean stratigraphy of Kent quadrangle, Trans-Pecos Texas: American Association of Petroleum Geologists Bulletin, v. 42, no. 2, p. 371-386.
- Cleveland, W.S., and McGill, R., 1984, The many faces of a scatterplot: *Journal of the American Statistical Association*, v. 79, p. 807-822.
- Dutton, A.R., and Simpkins, W.W., 1986, Hydrogeochemistry and water resources of the Triassic Lower Dockum Group in the Texas panhandle and eastern New Mexico: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 161, 51 p.
- Fenneman, N.M., 1931, *Physiography of western United States*: New York, McGraw-Hill, 534 p.
- Forgotson, J.M., Jr., 1957, Stratigraphy of Comanchean Cretaceous Trinity Group: American Association of Petroleum Geologists Bulletin, v. 41, no. 10, p. 2,328-2,363.
- Helsel, D.R., and Hirsch, R.M., 1992, *Statistical methods in water resources*: New York, Elsevier, 522 p.
- Hem, J.D., 1985, *Study and interpretation of the chemical characteristics of natural water* (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.
- Kuniansky, E.L., 1990, Potentiometric surface of the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas, winter 1974-75: U.S. Geological Survey Water-Resources Investigations Report 89-4208, 2 sheets.
- Kuniansky, E.L., and Holligan, K.Q., 1994, Simulations of flow in the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas: U.S. Geological Survey Water-Resources Investigations Report 93-4039, 40 p.
- LaFave, J.I., and Sharp, J.M., Jr., 1987, Origins of ground water discharging at the springs of Balmorhea: *West Texas Geological Society Bulletin*, v. 26, no. 9, p. 5-14.
- Loucks, R.G., 1977, Porosity development and distribution in shoal-water carbonate complexes—subsurface Pearsall Formation (Lower Cretaceous) south Texas, in *Bebout, D.G., and Loucks, R.G., eds., Cretaceous carbonates of Texas and Mexico, applications to subsurface exploration*: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 89, p. 97-126.
- Lozo, F.E., Jr., and Stricklin, F.L., Jr., 1956, Stratigraphic notes on the outcrop basal Cretaceous, central Texas: *Transactions of the Gulf Coast Association of Geological Societies*, v. 6, p. 67-78.
- Maclay, R.W., Rettman, P.L., and Small, T.A., 1980, Hydrochemical data for the Edwards aquifer in the San Antonio area, Texas: Texas Department of Water Resources LP-131, 38 p.
- Maley, V.C., and Huffington, R.M., 1953, Cenozoic fill and evaporite solution in the Delaware basin, Texas and New Mexico: *Geological Society of America Bulletin*, v. 64, p. 539-546.
- Nalley, G.M., and Thomas, M.W., 1990, Compilation of hydrologic data for the Edwards aquifer, San Antonio area, Texas, 1989, with 1934-89 summary: *Edwards Underground Water District Bulletin* 49, 155 p.
- Nativ, Ronit, and Gutierrez, G.N., 1988, Hydrogeology and hydrochemistry of Cretaceous aquifers, Texas panhandle and eastern New Mexico: Austin, University of Texas, Bureau of Economic Geology Geological Circular 88-3, 32 p.
- Romanak, M.S., 1988, Sedimentology and depositional environment of the basement sand (Lower Cretaceous), west Texas: Arlington, University of Texas unpub. M.S. thesis, 143 p.
- Rose, P.R., 1972, Edwards Group, surface and subsurface, central Texas: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 74, 198 p.

- Sharp, J.M., Jr., 1989, Regional ground-water systems in northern Trans-Pecos Texas, *in* Structure and Stratigraphy of Trans-Pecos Texas—field trip guidebook T317, El Paso to Guadalupe Mountains and Big Bend, July 20-29, 1989: American Geophysical Union, Washington, D.C., p. 123-130.
- Smith, C.I., and Brown, J.B., 1983, Introduction to road log Cretaceous stratigraphy, *in* Kettenbrink, E.C., Jr., ed., Structure and stratigraphy of the Val Verde Basin-Devils River uplift, Texas: West Texas Geological Society Publication no. 83-77, p. 1-47.
- Stricklin, F.L., Jr., Smith, C.I., and Lozo, F.E., 1971, Stratigraphy of Lower Cretaceous Trinity deposits of central Texas: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 71, 63 p.
- Sun, R.J., ed., 1986, Regional aquifer-system analysis program of the U.S. Geological Survey—Summary of projects, 1978-84: U.S. Geological Survey Circular 1002, 264 p.
- Texas Department of Health, 1977 [revised 1990], Drinking water standards governing drinking water quality and reporting requirements for public water systems: Austin, Division of Water Hygiene, 34 p.
- U.S. Environmental Protection Agency, 1990, Drinking water regulations under the Safe Drinking Water Act, May 1990: Washington, D.C., Criteria and Standards Division, Office of Drinking Water, Fact sheet, 43 p.
- Walker, L.E., 1979, Occurrence, availability, and chemical quality of ground water in the Edwards Plateau region of Texas: Texas Department of Water Resources Report 235, 336 p.
- White, D.E., 1968, Ground-water resources of Upton County, Texas: Texas Water Development Board Report 78, 137 p.

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