CHARACTERISTICS OF STREAMS AND AQUIFERS AND PROCESSES AFFECTING THE SALINITY OF WATER IN THE UPPER COLORADO RIVER BASIN, TEXAS

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
barrel (bbl)	158.97	liter
barrel per day (bbl/d)	158.97	liter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
million gallons per day (Mgal/d)	3,785	kiloliter per day
pound per square inch (lb/in^2)	6,892.8	pascals
ton	907.18486	kilogram
ton per day (ton/d)	907.18486	kilogram per day
ton per day per square mile [$(ton/d)/mi^2$]	350.4	kilogram per day per square kilometer
ton per day per cubic foot per second [$(ton/d)/(ft^3/s)$]	28.773	kilogram per day per cubic meter per second
	Temperature	
degree Fahrenheit (°F)	5/9 x (°F - 32)	degree Celsius

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

Agencies:

BEG, University of Texas, Bureau of Economic Geology
SCS, U.S. Soil Conservation Service
TDH, Texas Department of Health
TNRCC, Texas Natural Resource Conservation Commission (fomerly Texas Water Commission)
TWDB, Texas Water Development Board (formerly Texas Department of Water Resources)
USEPA, U.S. Environmental Protection Agency
TWODB, Texas Water Oriented Data Bank
USGS, U.S. Geological Survey

Water Quality:

°C, degree Celsius
g, gram
MCL, maximum contaminant level
µS/cm, microsiemens per centimeter at 25 °C
mg/kg, milligram per kilogram
mg/L, milligram per liter
SMCL, secondary maximum contaminant level

Characteristics of Streams and Aquifers and Processes Affecting the Salinity of Water in the Upper Colorado River Basin, Texas

By Raymond M. Slade, Jr., *and* Paul M. Buszka

Abstract

The upper Colorado River and some of its tributaries between Lake J.B. Thomas and O.H. Ivie Reservoir contain saline water (defined as water having dissolved-solids concentrations greater than 1,000 milligrams per liter). Dissolved-solids loads at nine streamflow water-quality stations increased from 1986 to 1988. The largest increases were in Beals Creek and in the Colorado River downstream from Beals Creek as a result of outflow of saline water from Natural Dam Salt Lake. The outflow contained 654,000 tons of dissolved solids and had a mean dissolved-solids concentration of 7,900 milligrams per liter. This amount represents about 51 percent of the dissolved-solids load to E.V. Spence Reservoir during 1986-88.

The concentration of dissolved solids in streamflow in the upper Colorado River, however, generally decreased in the downstream direction as flows increased in all reaches of the river and its tributaries. Diversion of low flows at a site on the Colorado River upstream from the E.V. Spence and O.H. Ivie Reservoirs decreased the dissolved-solids concentrations of inflow to the reservoirs by about 7 percent while removing only about 3 percent of the total flow. The estimated dissolved-solids concentration exceeded 1,000 milligrams per liter for water from about 233 of 386 wells and springs for which specific conductance was measured in 1986. The mean value of the estimated dissolved-solids concentration for water from the 386 wells and springs was about 1,750 milligrams per liter.

Some of the dissolved-solids content of streamflow and shallow-aquifer water was attributed to evapotranspiration in areas where water was close to land surface, in irrigated areas, and along streams. The evapotranspiration was largely from phreatophytes and was comparable to the mean streamflow from the study area during 1969-86. However, evapotranspiration was not considered to have an effect on the salinity of water in shallow aquifers on a regional scale. Dissolution of sulfur-bearing minerals such as gypsum and pyrite in shallow aquifers contributed to salinity because of their presence in soil and shallow-aquifer formations.

Mixing with brine associated with oil and gas production is a major process affecting the salinity of streamflow and shallow-aquifer water. Brines can move upward through the more than 20,000 abandoned oil- and gas-related boreholes, most of which were abandoned prior to current requirements for casing, cementing, and plugging. Leakage from pits, disposal wells, and secondary-recovery wells, which have been used to dispose of brine, a by-product of oil and gas production, also contributed to dissolved solids in streamflow and shallow-aquifer water. The ratio of brine production to oil production in the seven major oil-producing counties increased from 0.60 to 6.5 between 1957 and 1983. About 359 million barrels of brine were injected into oil-producing formations through secondary-recovery wells in 1983, compared to 11 million barrels through disposal wells.

The chemical characteristics of the saline water in streams and shallow aquifers in the study area were compared to characteristics of water that would result from the probable processes affecting the salinity of water, such as evapotranspiration, mineral dissolution, and mixing of water from streams and shallow-aquifer water with brines from deep aquifers. Dissolution of halite or mixing with deep-aquifer water was the most common cause of increased salinity in 48.0 percent of 77 water samples from shallow aquifers, as classified using salt-norm analysis; the second most common cause was the weathering and dissolution of sulfur-bearing minerals. Mixing with water from soil-mineral dissolution was classified as the principal source of chloride in 28.4 percent of 67 water samples from shallow aquifers with nitrate determinations. Trace-species/chloride ratios indicated that mixing with water from deep aquifers in rocks of the Pennsylvanian System was the principal source of chloride in 24.4 percent of 45 shallow-aquifer samples lacking nitrate determinations.

INTRODUCTION

The upper Colorado River and some of its tributaries between Lake J.B. Thomas and O.H. Ivie Reservoir (fig. 1) contain saline water (defined as water in which the dissolved-solids concentrations are greater than 1,000 mg/L). The salinity gradually decreases downstream as tributaries contribute water containing lower concentrations of dissolved solids to the river in its 841-mi course from Lake J.B. Thomas to the Gulf of Mexico.

Streamflow and water from the shallow-aquifer system are the sole sources of water for municipal, irrigation, domestic, and thermoelectric use in the upper Colorado River Basin. Because the dissolved-solids concentrations in the water limit its use, several ongoing water-quality management programs and remedial projects in the area have been designed to reduce dissolved-solids loads to the Colorado River. Nevertheless, Andrews and Schertz (1986) reported a large increase in the dissolved-solids concentrations in streamflow from 1973 to 1982 at three water-quality stations in the upper Colorado River watershed. All three stations are upstream from E.V. Spence Reservoir, which provides water to the surrounding area, and upstream from O.H. Ivie Reservoir, near the confluence of the Colorado and Concho Rivers (fig. 1). O.H. Ivie Reservoir, completed and filled in 1992, is expected to supply 113,000 acre-ft of water annually for municipal, industrial, and domestic uses (U.S. Army Corps of Engineers, 1986) to much of west-central Texas.

The large increases in dissolved-solids concentrations of the Colorado River have caused concern about the quality of water in O.H. Ivie Reservoir. To address these concerns, the U.S. Geological Survey (USGS), in cooperation with the Colorado River Municipal Water District, began a study in October 1985 to improve and extend knowledge of the amount, extent, and movement of dissolved solids in streams and aquifers in the upper Colorado River Basin between Lake J.B. Thomas and O.H. Ivie Reservoir, and to determine the probable sources of the dissolved solids. The study included inventorying and tabulating oil- and gas-field data, conducting a literature search to obtain historical water-resources data, locating and inventorying water wells and springs in the study area, making water-level measurements, and analyzing the chemistry of the water. The period of collection and analysis of the data was from October 1985 to about 1990.

Purpose and Scope

The purpose of this report is to describe the characteristics of streams and aquifers and the processes affecting the salinity of water in the upper Colorado River Basin through about 1990. Characteristics of streams were determined using historical records primarily from 1969-86, and from data collected in the study area from 1986-88. Characteristics of aquifers were determined using historical records through about 1990, and from data collected in the study area in 1987 and 1989. A brief final section of the report discusses the relation of salinity classifications to oil and gas production.

Description of Study Area

The study area contains the watershed that contributes most of the flow to O.H. Ivie Reservoir and includes a 240-mi reach of the Colorado River from Lake J.B. Thomas to O.H. Ivie Reservoir near Stacy (fig. 1). Other than two releases for flood outflows, no water has been released from Lake J.B. Thomas since its completion in 1952. The watershed upstream from the lake, therefore, is almost always noncontributing to the river system.

Three major tributaries, Beals Creek, Elm Creek, and the Concho River, contribute substantial flow to the

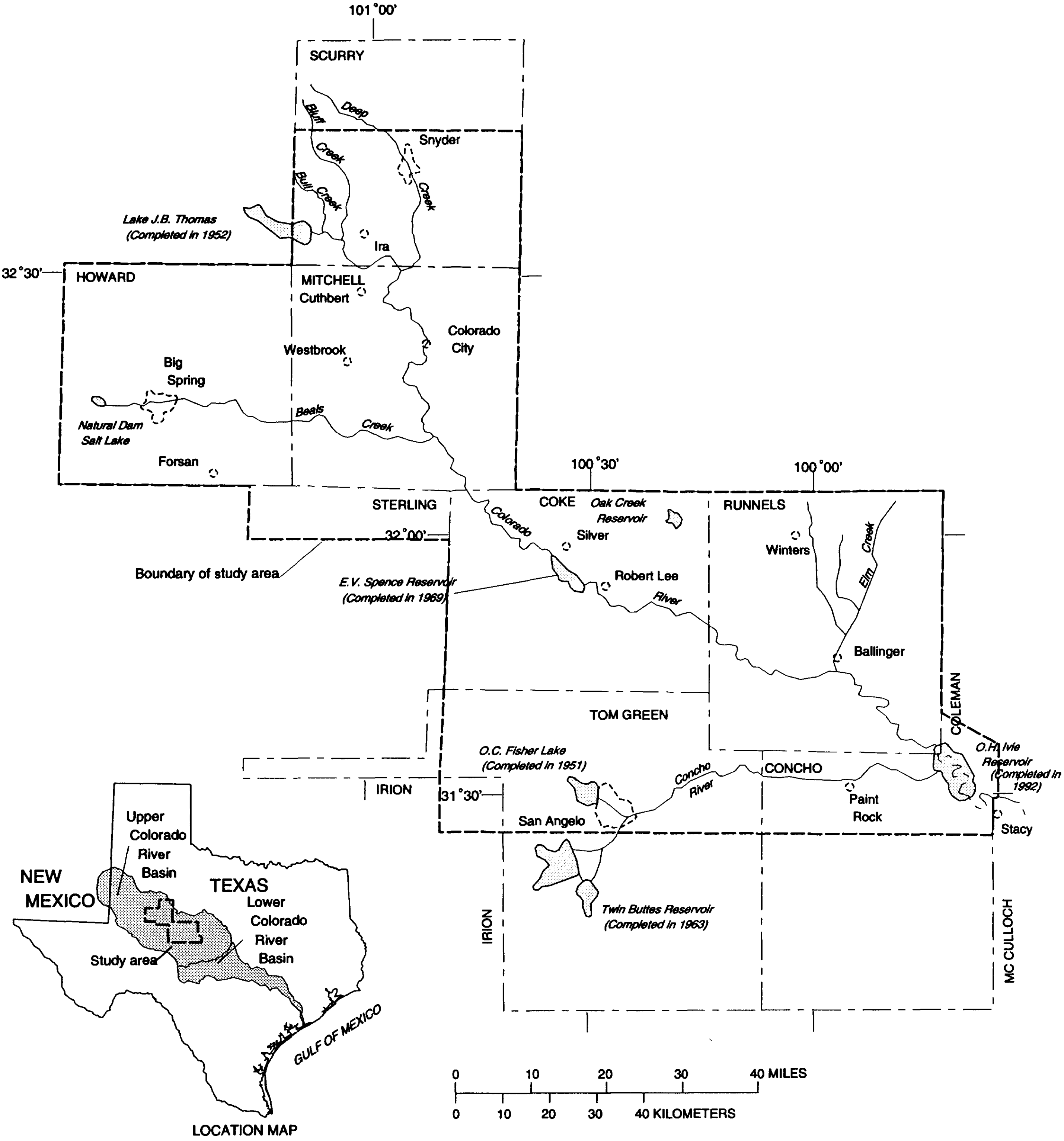


Figure 1. Location and extent of the study area.

Colorado River in the study area. Most of the contributing watersheds to these streams are included in the study area. Flow seldom enters the study area from Beals Creek upstream from Big Spring, and most of the flow in the Concho River originates downstream from San Angelo; therefore, most of the area upstream from Big Spring and San Angelo was not included in the study area. The areas adjacent to the Colorado River and the three tributaries are included because minor tributary and aquifer discharges contribute to the flows in these streams.

Data available by county only are included throughout the report. Only four counties (Coke, Howard, Mitchell, and Runnels) are entirely within the study area. In most sections of the report, county totals include data for Coke, Concho, Howard, Mitchell, Runnels, Scurry, and Tom Green counties, an area of about 7,260 mi^2. All or large parts of these counties are in the study area, and are referred to as major counties in this report. Small parts of Coleman, Irion, and Sterling Counties also are in the study area, but their contribution to the watershed is minor. Some material used in this report contains data from the three minor counties.

Physiographic Setting and Climate

The study area is characterized by low rolling hills covered with mesquite and prairie grasses, and occasional prominent mesas. Altitudes range from about 1,400 ft above sea level at the downstream end of the study area, to about 2,800 ft above sea level at the northwest corner of Howard County. Slopes range from less than 0.5 percent in upland areas away from the Colorado River to sheer bluffs along the river with cliffs about 100 ft high. The bed of the Colorado River is incised deeply into surrounding lands because erosion from streamflow has caused steep slopes near the mouth of many of its tributaries. The mean gradient of the Colorado River in the study area is about 3.3 ft/mi; slopes range from about 3.8 ft/mi near Lake J.B. Thomas to about 2.9 ft/mi near O.H. Ivie Reservoir.

The climate is semiarid. Long, hot summers and moderate winters exhibit a large range of temperatures. Mean-maximum temperatures range from the mid-50's in January to the mid-90's in July, and mean-minimum temperatures range from about 32 °F in January to about 70 °F in July and August. The mean-annual temperature ranges from about 63 °F in the northern part to about 66 °F in the southern part (Carr, 1967).

The mean-annual precipitation for 1951-80 is about 16 in. at the western boundary of Howard County and increases eastward to about 25 in. at the eastern boundary of the study area (Gebert and others, 1987). Mean-annual precipitation for this period is within 1 in. of the 1931-60 mean (Carr, 1967). Most precipitation in the area is from thunderstorms during the spring and fall. Annual precipitation varies substantially throughout the area--less than 10 in. during dry years and more than 40 in. during wet years. Long-term droughts are common over small and large parts of the area.

Soils over most of the study area are characterized by red to brown sands and clays formed in outwash or over limestones. These soils support dry cropland and rangeland grasses in about 40 and 60 percent of the area, respectively. However, as of 1985, only 1,300 mi^2, or 18 percent of the 7,260 mi^2 of the seven major counties had been planted with crops; about 1 percent of the total area is irrigated cropland (Texas Agricultural Statistics Service, 1985). No forest lands, wetlands, or barren lands are present in the study area.

Water Use

County-wide freshwater use for the seven major counties averaged about 276 Mgal/d in 1985. All water-use data for the study area were supplied by D.L. Lurry (U.S. Geological Survey, oral commun., 1990). Freshwater supplied the needs of about 181,000 people. The use of water probably is increasing slightly along with the population--the 1960 population for the area was about 159,000 and the 1980 population was about 163,000 (Dallas Morning News, 1987).

County water use, by categories, is shown in figure 2. Total surface-water use, about 230 Mgal/d, or about 84 Mgal/d excluding thermoelectric use, greatly exceeded the total ground-water use of about 46 Mgal/d. Thermoelectric use, which accounted for more than one-half of total water use, represents surface-water withdrawals to cool generators at four fossil-fuel power-generating plants. Public supply and irrigation accounted for most of the remaining use. The 62.9 Mgal/d for public supply served about 90 percent of the population; the remaining 10 percent was served by domestic water supplies. The 54.6 Mgal/d of irrigation water was applied to about 53,600 acres in the area. About 64 percent of irrigation came from ground water, and the remaining 36 percent came from surface water.

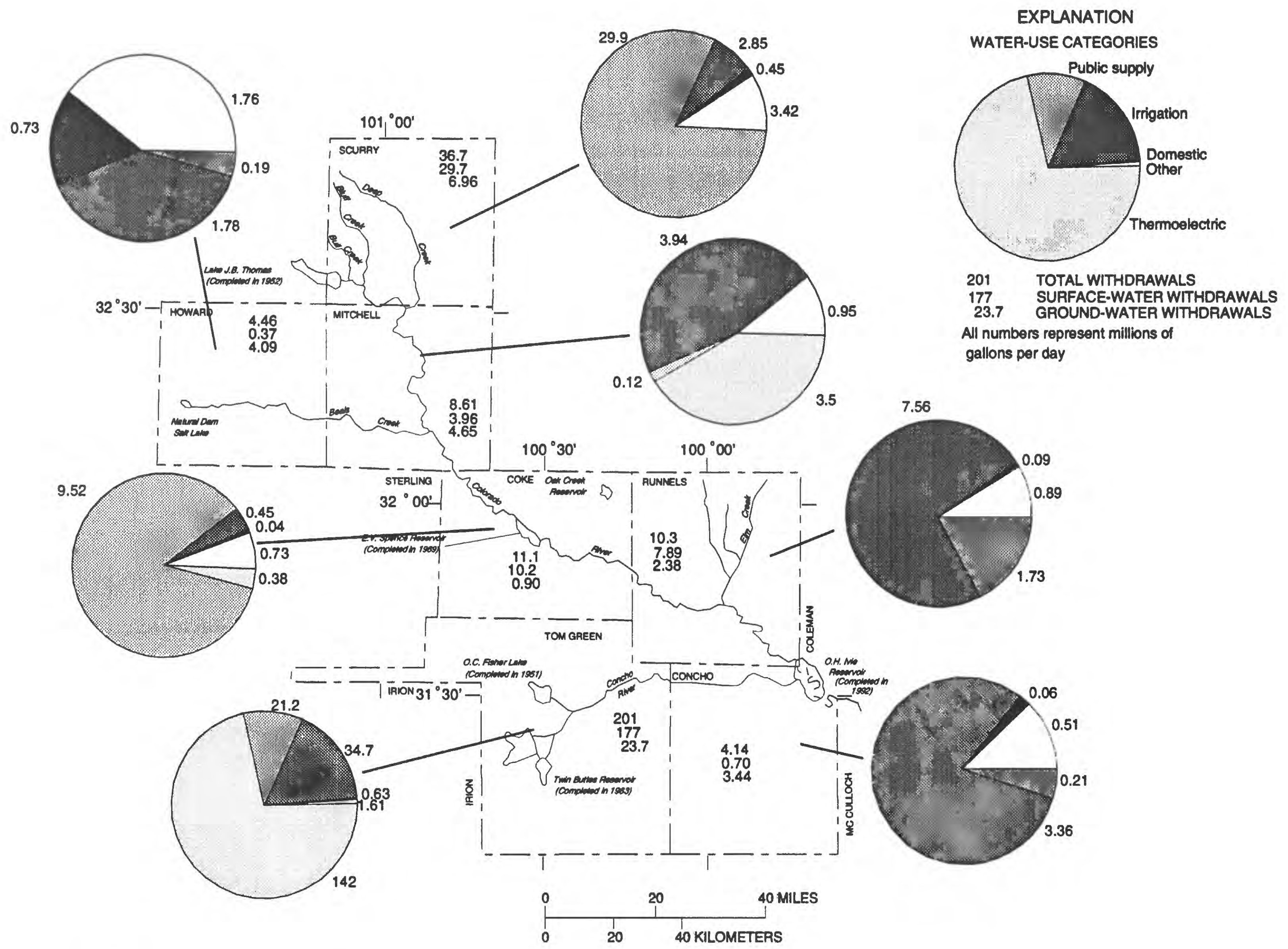


Figure 2. County water use by categories, 1985.

Almost 64 percent of the total irrigation was in Tom Green County.

Well-Numbering System

The well-numbering system in this report was adapted from the system developed by the TWDB. It is based on the latitude and longitude of the well or spring and consists of a seven-digit number. The county prefix, which is part of the TWDB numbering system, was omitted in this report to shorten the number.

Each 1-degree quadrangle in the State is given a number consisting of two digits from 01 through 89. These are the first two digits of the well or spring number. The study area spans five 1-degree quadrangles--28, 29, 30, 42, and 43. Each 1-degree quadrangle is divided into 7-1/2-minute quadrangles that are given two-digit numbers from 01 through 64. These are the third and fourth digits of the number. Each 7-1/2-minute quadrangle is divided into 2-1/2-minute quadrangles that are given a single-digit number from 1 through 9. This is the fifth digit of the number. Within the 2-1/2-minute quadrangles, each well or spring is given a two-digit number beginning with 01, according to the order it was inventoried. These are the last two digits of the number.

Acknowledgments

The authors acknowledge the many property owners who supplied information and permitted access to their property. The TWDB (Texas Water Development Board) furnished historical water-level and water-quality data for wells and springs in the area. Technical assistance was provided by Mr. Bernd Richter of the BEG (University of Texas, Bureau of Economic Geology). The Colorado River Municipal Water District also provided information for the study.

Special acknowledgment is given to Mr. James Shotwell, a petroleum geologist from Midland. As a member of the Volunteer Program for the USGS, Mr. Shotwell donated his efforts to review the oil-field data used in this study. Special acknowledgment also is given to Ms. Rachel Martinez of Austin for her contributions as a member of the Volunteer Program. Ms. Martinez, a petroleum geologist, also reviewed the data on oil-field activities.

INTERPRETIVE METHODS FOR CLASSIFICATION OF WATER SALINITY

Methods of interpreting water-quality data to identify and describe the processes affecting salinity of water are described in the following sections. Summary statistics were computed to describe the variation in quality of water from deep aquifers. Mineral-saturation indices were computed to define possible mineralogic influences on salinity. Salt norms were computed to evaluate potential processes affecting salinity. Trace-species/chloride ratios and chloride concentrations were plotted on "mixing diagrams" to determine the most plausible origins of dissolved-solids and chloride concentrations in the streamflow and shallow-aquifer water.

The terms Permian System water and Pennsylvanian System water are used throughout the report to describe water from several deep aquifers within those geologic systems. These terms were applied when a chemical characteristic was similar among the aquifers in a geologic system.

The following descriptions of water salinity from Winslow and Kister (1956) were used for the associated dissolved-solids concentrations throughout the report:

Salinity classification	Dissolved-solids concentration (milligrams per liter)
Freshwater	Less than 1,000
Saline water	Greater than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	Greater than 35,000

The data were compiled using: (1) Analysis of water samples collected during this study in 1987 and 1989 (table 1 at end of report); (2) selected data in published reports of the BEG (Richter and Kreitler, 1985; Dutton and Simpkins, 1986; and Richter and others, 1990); and (3) unpublished data from deep aquifers obtained from Petroleum Information Corp., Denver, Colorado (written commun., 1990). Locations of wells and springs sampled and water-quality data compiled from BEG reports are presented in the reports cited in (2) above. The identification numbers for wells and springs reported in the BEG reports are referred to in this report by the same 1- or 2-digit number as in the original BEG reports.

Water-quality data collected in 1987 from nine streamflow-study sites (pl. 1) that were flowing during times when the sites were visited were included in the analyses (table 1). Water-quality data for shallow aquifers included all USGS analyses with bromide determinations, and the most recent of the analyses from wells and springs sampled by the BEG. Analyses having a balance of cation to anion charge within 10 percent were used in the analyses.

Concentrations of dissolved solids, and the major inorganic constituents of deep aquifers in the study area were obtained from Core Laboratories, Inc., (1972b) and Beeler and others (1975). Results of some brine analyses also were obtained from a few of the many ground-water reports listed in the selected references. On the basis of their data, Core Laboratories, Inc., (1972b) constructed isopleths of dissolved-solids concentrations for water in several deep aquifers, and McNeal (1965) constructed isopleths of dissolved-solids concentrations for water in five of the deep aquifers.

Most of the water-quality data for the deep aquifers used in this report are from Petroleum Information Corp. (written commun., 1990). These data contain identification, location, well information, and water-quality analyses for brines sampled during testing of oil and gas wells. A total of 510 analyses for dissolved solids were compiled from Petroleum Information Corp.; 21 analyses were available from samples collected and analyzed by the BEG (Richter and Kreitler, 1985, and Richter and others, 1987); and 3 analyses were available from samples collected and analyzed by the USGS in August 1987. Only analyses with a cation-anion balance within 10 percent were used. The resulting 534 water-quality analyses for deep aquifers are referred to in this report as the brine analyses file. Analyses, without chloride determinations, of water from two deep-aquifer wells, the Coleman Junction Limestone oil well and the SSR oil well, also were used in the water-quality characterization (table 1). Chloride concentrations were estimated for water from these two wells by setting them equal to the difference between cation and anion charge.

Analytical methods used to determine common ion, inorganic constituents, and nutrient species in samples collected during this study are documented by Fishman and Friedman (1985). Total organic carbon analyses were made using techniques described by Wershaw and others (1987). Water samples collected by the BEG were preserved and analyzed using methods described by Dutton (1989) and generally were consistent with USGS procedures. Analytical methods for proprietary data obtained from the Petroleum Information Corp. (written commun., 1990) are not documented in this report.

Mineral-Solubility Analysis

The potential for rock-water interactions to affect the salinity of streamflow and shallow-aquifer water was evaluated using water-quality data and the computer program SOLMINEQ.88 (Kharaka and others, 1988). The program provides a thermodynamic analysis of the data by computing the distribution of aqueous species and the degree of mineral saturation.

Mineral saturation is defined as the ratio of the ion-activity product of a given mineral to the theoretical solubility product of the same mineral. The ion-activity product represents the presence or "activity" of dissolved ions in solution that contribute to precipitation of a mineral, after correcting the original concentration for formation of complexes and pairs of associated ions in solution. The theoretical solubility product of a mineral is the ion-activity product developed by dissolving a mineral to equilibrium. The degree of mineral saturation commonly is represented as the logarithm of this ratio, referred to as the saturation index. Values of zero for the saturation index indicate equilibrium saturation for a given mineral; values greater than zero indicate oversaturation; and values less than zero indicate undersaturation. Saturation-index values between -0.5 and +0.5, but not equal to zero, are referred to as near saturation.

The dissolution of minerals, principally gypsum ($CaSO_4 \cdot 6H_2O$), calcite ($CaCO_3$), dolomite [$CaMg(CO_3)_2$], and halite (NaCl), was considered among possible sources of dissolved solids in streamflow and shallow-aquifer water. Saturation indices computed for these minerals by SOLMINEQ.88 were compared with the lithology and mineralogy of the study area to determine if any of these minerals were major contributors to salinity in water. Dissolution and oxidation of sulfide minerals such as pyrite (FeS), a possible source of sulfate in water, could not be considered in this analysis because of the lack of sulfide, ferrous iron, and total iron determinations.

The data for the SOLMINEQ.88 analysis were collected from analysis of samples from streams, shallow aquifers, and deep aquifers. Because the ionic strength of most water from deep aquifers was greater than 1 molal, all calculations of activities of dissolved ions were made using the Pitzer equations (Kharaka and others, 1988) and the July 11, 1989, revision of the USGS SOLMINEQ.88 mineral and coefficient data set (Jeffrey D. DeBarral, U.S. Geological Survey, written commun., 1989). An ionic strength of 1 molal is approximately equal to 58.5 g of dissolved solids as sodium chloride in 1,000 g of water. This approach enabled calculation of the saturation state for all water-quality constituents using the same program, regardless of salinity.

Salt-Norm Analysis

Salinity variations and potential processes affecting salinity were evaluated using "salt norms" calculated from water-quality data using the computer program SNORM (Bodine and Jones, 1986). The salt norm is the quantitative, ideal equilibrium salt assemblage that would crystallize if the water was evaporated to dryness at 25 °C and 14.5 lb/in^2 pressure under atmospheric partial pressure of carbon dioxide. The salt norms, reported as anhydrous weight percentages of normative minerals, are not actual solid phases or minerals. The salt norms make up an imaginary set of normative minerals that are related to the proportion of anions and cations in a water analysis.

The proportions of the normative minerals in a salt norm can be used to identify three major categories of water on the basis of salinity. "Meteoric-CO_3" or "Meteoric-SO_4" water ranges from freshwater to moderately saline and principally contains alkali-bearing carbonate and sulfate normative minerals. Marine-like water classified as "brine," "gypsum," or "HS-mixed" is chloride or sulfate rich and contains some or all of the normative minerals halite, bischofite ($MgCl_2 \bullet 6H_2O$), carnallite ($KMgCl_3 \bullet 6H_2O$), and anhydrite ($CaSO_4$); and alkali or magnesium sulfates. The Meteoric-SO_4 and "gypsum" water derives salinity from the dissolution of sulfate or sulfur-bearing minerals. The marine-like water can originate by mixing with deep- and shallow-aquifer brine, by dissolution of halite (brine) or gypsum or anhydrite (gypsum), or by evaporative concentration of water (HS-mixed). Diagenetic water, classed as "brine-mixed," yields a salt norm that contains the chloride normative minerals antarcticite ($CaCl_2 \bullet 6H_2O$) and tachyhydrite ($CaMg_2Cl_6 \bullet 12H_2O$). The diagenetic water is associated with a deep sedimentary basin or a deep aquifer and indicates the secondary reaction of a chloride rich brine with aquifer minerals.

Trace-Species/Chloride Ratios

The principal sources of chloride in streamflow and shallow-aquifer water also were classified using equivalent ratios of chloride/nitrate and weight ratios of bromide/chloride. The most likely process affecting chloride content in water was inferred by the similarity of these ratios to those of ideal mixtures between water with small chloride concentrations and four known, potential sources of chloride: (1) Water affected by dissolution of soluble salts from the unsaturated zone; (2) water from Pennsylvanian System deep aquifers; (3) water from Permian System deep aquifers; and (4) water affected by halite dissolution. Chloride is present in large concentrations in many brines from deep sedimentary basins and in saline water affected by halite dissolution and evaporative concentration (Bodine and Jones, 1986). Trace-species/chloride ratios have been used to indicate the process affecting chloride concentrations because bromide and chloride are unaffected by most mineral-water interactions (Whittemore, 1988). Nitrate also is not affected by most mineral-water interactions under the strongly oxidizing conditions that commonly are present in shallow-aquifer water, in fractured rock, or very permeable sediment (Freeze and Cherry, 1979, p. 413-414).

Chloride/nitrate (Cl/NO_3) equivalent ratios were used to indicate the relative importance of soil-mineral dissolution to chloride concentrations in water. The principal sources of nitrate in shallow-aquifer water are dissolution of mineralized nitrate or animal-waste derived nitrate from the unsaturated zone (Kreitler and Jones, 1975; and Richter and others, 1987). This study interpreted Cl/NO_3 ratios of less than about 10 as representing the leaching of unsaturated-zone salts into water. Samples with Cl/NO_3 ratios larger than about 20 were interpreted as affected by other processes. Processes affecting salinity in these latter samples were investigated using bromide/chloride weight ratios.

Mixing curves based on bromide/chloride weight ratios with respect to chloride were drawn to determine the similarity between: (1) Water quality from streamflow and shallow aquifers; and (2) mixtures of differing amounts of water with small chloride concentrations, water from Permian System and Pennsylvanian System deep aquifers, and brines originating from dissolution of halite. A similarity between the quality of a water and one or more of the ideal mixtures is circumstantial evidence of the source of that sample's chloride content.

The ideal mixing curves (fig. 3) were constructed using the equation (Whittemore, 1988):

$$C(mix) = C(1) \times V + C(2) \times (1-V), \qquad (1)$$

where C(mix) = concentration of trace species or chloride in the ideal mixture;

C(1) = concentration of trace species or chloride in water with small chloride concentrations;

C(2) = concentration of trace species or chloride in water from deep aquifers or halite dissolution brine; and

V = volumetric fraction in ideal mixture of water with small chloride concentrations.

Ratios of Br/Cl and chloride concentrations in water from streams and shallow aquifers then were superimposed on figure 3 to identify their positions relative to the mixing curves. Where Br/Cl weight ratios and chloride concentrations in a sample coincided with a mixing curve, the source of the chloride was classified as the brine used to define the mixing curve. For example, a sample that plots inside the mixing curve between water with small chloride concentrations and halite dissolution brine is classified as obtaining its chloride from halite dissolution.

The weight ratios of Br/Cl have been used by other investigators to characterize brine among the following types: deep-basin brine, brines originating from oil- and gas-field contamination, and halite dissolution brine (Whittemore and Pollock, 1979; and Richter and Kreitler, 1986 and 1987). Weight ratios of Br/Cl typically are larger in oil- and gas-field brines than in halite dissolution brines (Whittemore, 1988). Bromide can be added to solution through the decomposition of organic matter and the leaching of soluble minerals such as from caliche deposits enriched in bromide (Whittemore, 1988). Bromide is incorporated into halite in a trace proportion that is 10 times less than chloride (Holser, 1979, p. 298). Weight ratios of Br/Cl are discussed as multiples of 10,000 to enable comparison to other reported values.

Lower and upper limits for ideal mixing curves were defined (fig. 4) using analyses reported in this study and published data from the BEG and other studies (Whittemore and Pollock, 1979; and Dutton, 1989). The range of Br/Cl ratios in water with small chloride concentrations was defined using data from water analyses with less than 200 mg/L of chloride. Lower and upper limits for Br/Cl ratios for deep aquifers in Permian System and Pennsylvanian System formations were defined as the 25th and 75th percentiles of each distribution, respectively (table 2). Lower and upper limits of Br/Cl ratios for halite dissolution brines were defined using the minimum and maximum ratios from deep aquifers in Permian System formations in the Southern High Plains (Dutton, 1989, p. 79). These latter data were similar to those reported from the Permian System brine (table 2) from the Wellington Formation, Kansas (Whittemore and Pollock, 1979, p. 20).

The classified sources of chloride in this report assume areal uniformity in the chemistry of deep-aquifer waters and halite dissolution brines. These classifications do not account for potential local variations in the sources of chloride and their chemistry. The classified sources of chloride in individual water samples, therefore, must be verified by site-specific investigations.

CHARACTERISTICS OF STREAMS

Characteristics of streams were based on data from streamflow-gaging stations operated by the USGS throughout the study area. Historical stream discharges were available for 30 stations, and reservoir contents were available for 5 stations in the study area. However, only 10 of the streamflow stations and 2 of the reservoir stations were in operation, as of 1990 (Buckner and Shelby, 1990).

Streamflow

A common period (1969-86) was used to determine mean-annual precipitation at 11 gages and streamflow and runoff at 12 gaging stations (fig. 5). Gaging station 08123650 also was included, even though the period of record was 1969-78, because it provided data for the drainage area upstream from Big

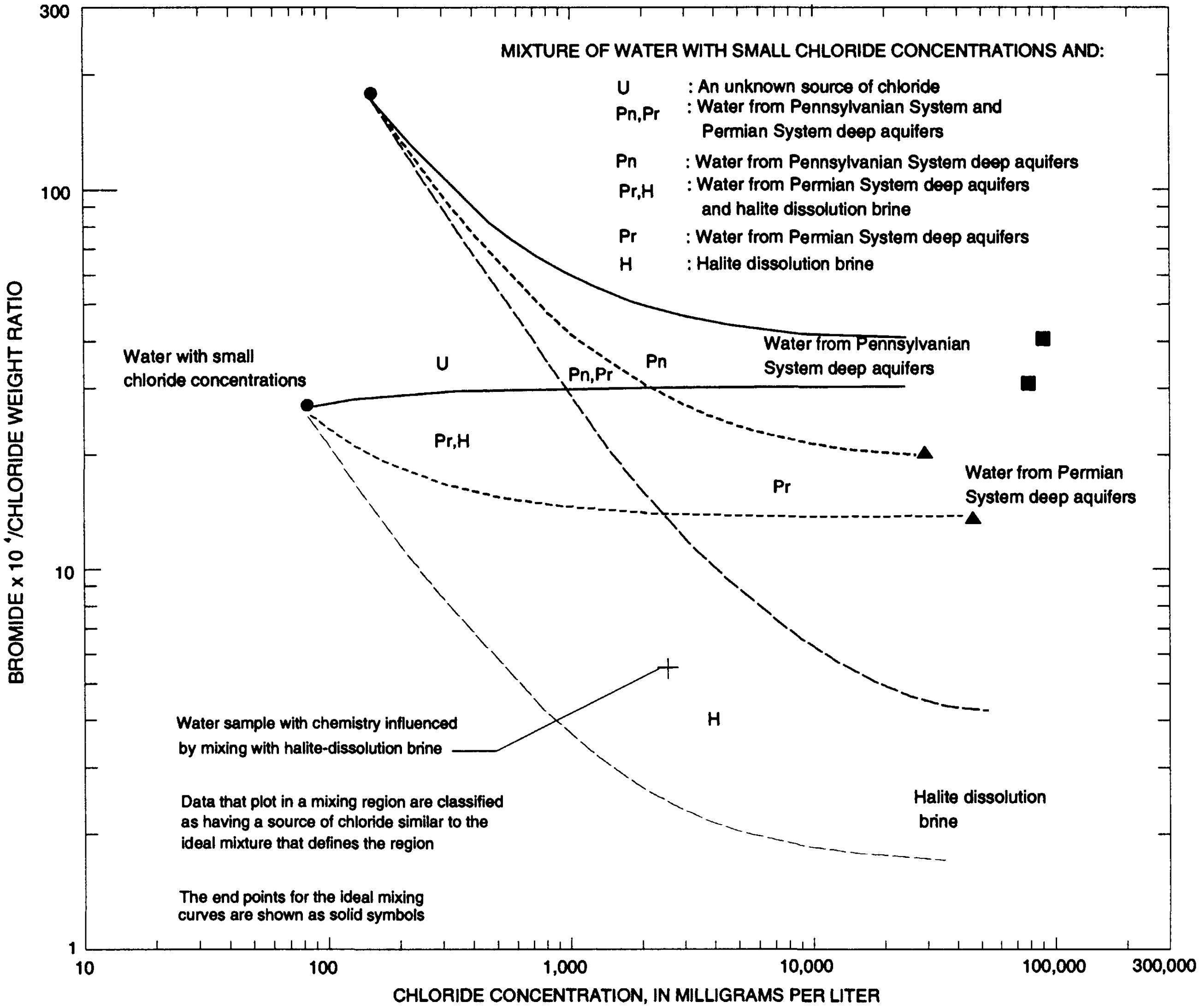


Figure 3. Guide to interpreting sources of chloride in water using ideal linear mixing curves based on bromide/chloride ratios and chloride concentrations. (Equation for curves from Whittemore, 1988; see p. 9 of text.)

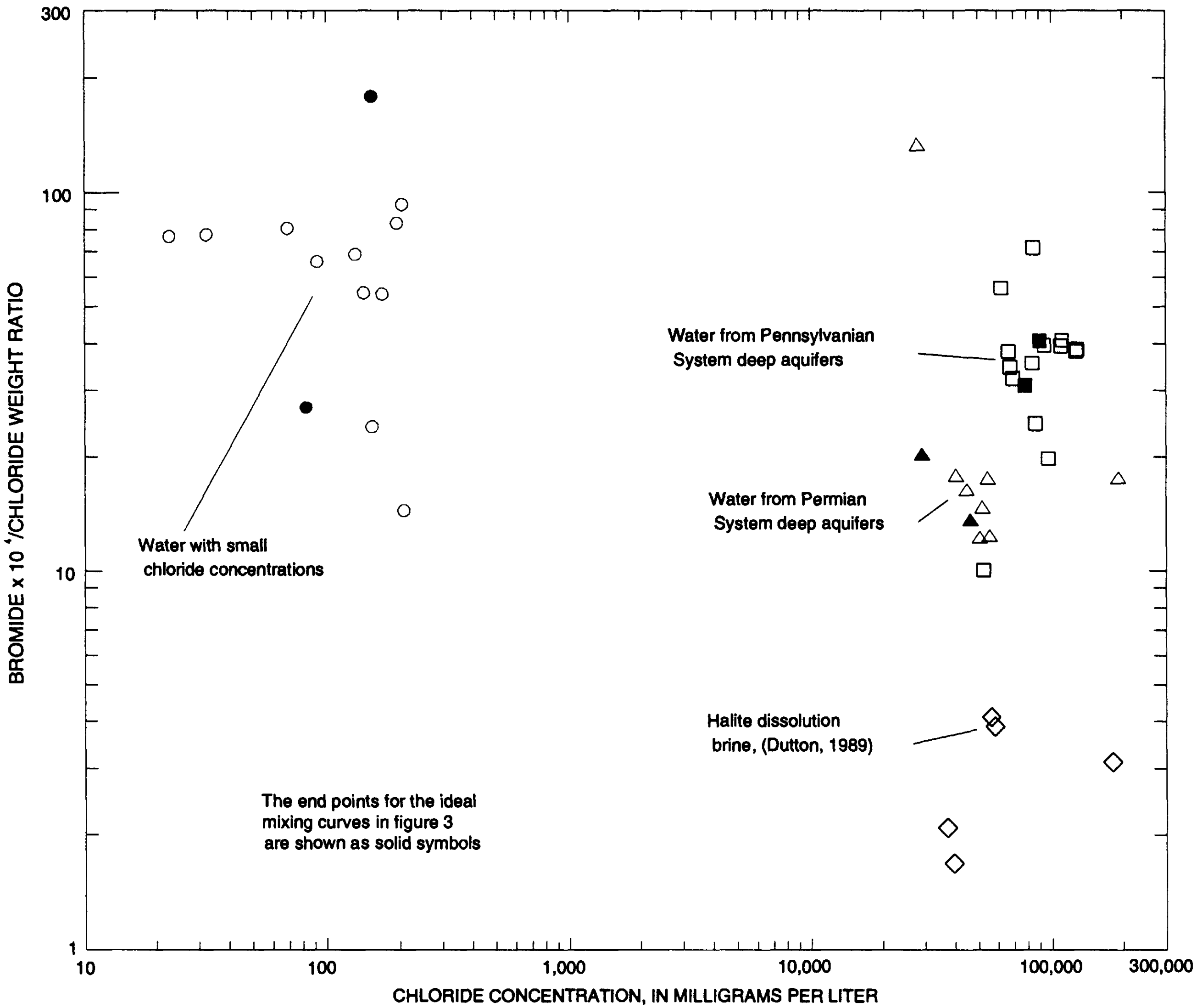
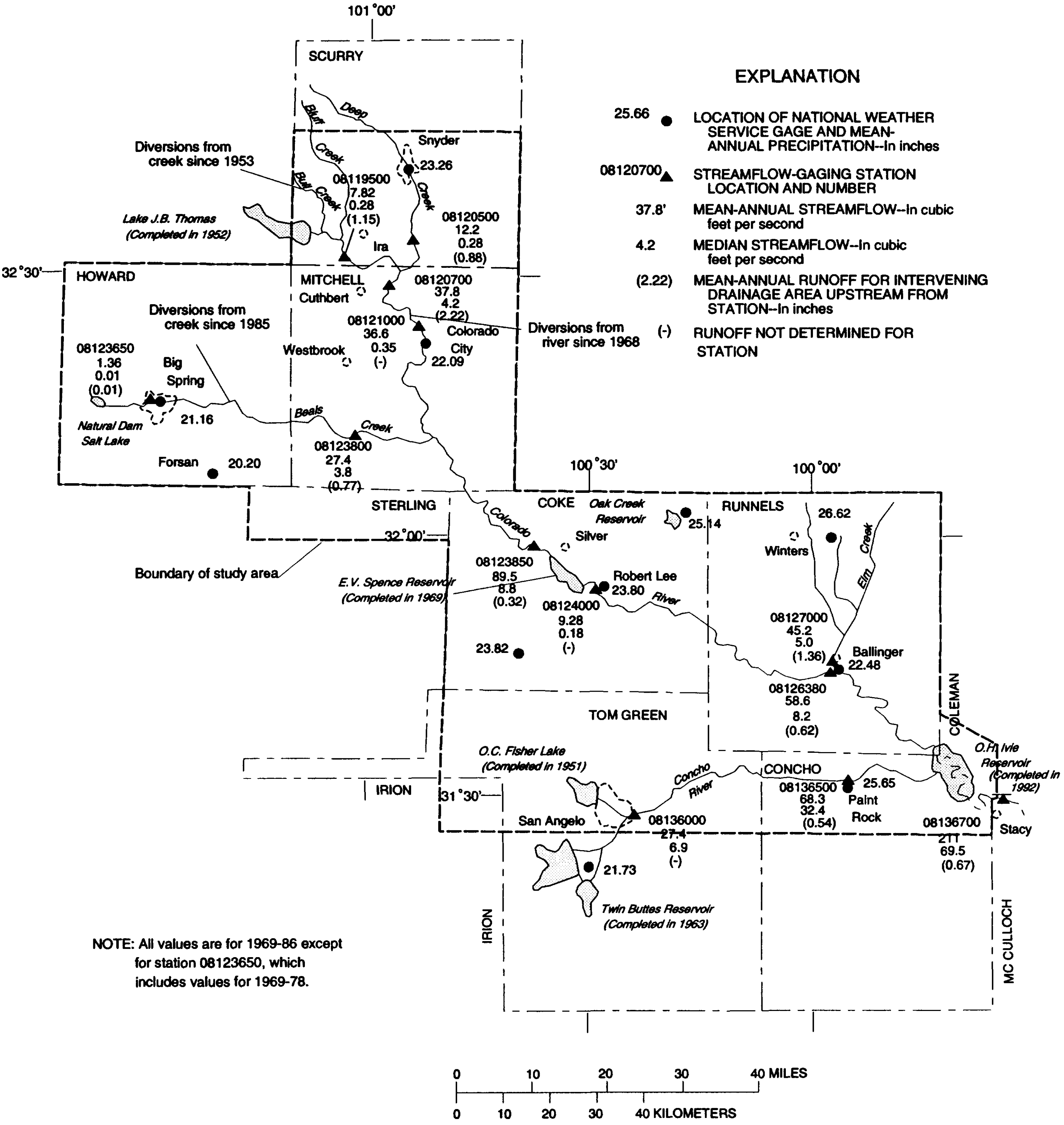


Figure 4. Water analyses used to define lower and upper limits for ideal mixing curves based on bromide/chloride weight ratios and chloride concentrations.



NOTE: All values are for 1969-86 except for station 08123650, which includes values for 1969-78.

Figure 5. Mean-annual precipitation and streamflow, median streamflow, and mean-annual runoff, 1969-86.

Table 2. Statistical summary of bromide/chloride weight ratios in water from deep aquifers and halite dissolution brines in the upper Colorado River Basin, Texas

[--, insufficient data to report statistic]

Water source and reference	Number of samples	Bromide x 10^4/chloride weight ratio				
		Minimum	25th percentile	Median	75th percentile	Maximum
Deep aquifers in Permian System formations, including Whitehorse-San Andres, San Angelo, Clear Fork, and Wolfcamp[1]	12	13	14	18	20	137
Deep aquifers in Pennsylvanian System formations, including Cisco, Canyon, and Strawn[1]	18	8.1	29	38	40	72
Halite dissolution brines:						
Deep aquifers in Permian System formations, Southern High Plains (Dutton, 1989, p. 9)	5	1.7	--	3.1	--	4.1
Permian System brine, Kansas (Whittemore and Pollock, 1979, p. 20)	3	1.0	--	3.1	--	4.1

[1] Water from the Whitehorse-San Andres, San Angelo, Clear Fork, and Wolfcamp deep aquifers also is collectively referred to in this report as "water from Permian System deep aquifers." Water from the Cisco, Canyon, and Strawn deep aquifers also is collectively referred to in this report as "water from Pennsylvanian System deep aquifers."

Spring. Analyses of the streamflow data shown in figure 5 were used to determine runoff characteristics. The streamflow data represent total runoff for most of the area. Of the three large off-stream diversions, only the diversions upstream from station 08121000 greatly affect streamflow. Numerous other diversions from the Colorado River and major tributary streams were small except during base-flow periods. These smaller diversions have only minimal effects on mean streamflow.

Mean-annual runoff for the intervening drainage areas between stations was calculated as the difference between the gaged runoff at a given station and the gaged runoff at the next station upstream from the given station, divided by the contributing drainage area between the stations. Large changes in the quantity of runoff resulting from human activity were not evident during 1969-86 except for diversions of low flow from Beals Creek since 1985. The mean-annual precipitation for 1969-86 was slightly greater than that reported by Gebert and others (1987) for 1951-80--about 3 to 4 in. greater in the western part of the study area and about 1.5 in. greater in the eastern part. Therefore, runoff during 1969-86 may have been slightly greater than the long-term means.

The runoff, as a percentage of precipitation, can be estimated by comparing the mean-annual runoff to the mean-annual precipitation (fig. 5). Runoff, as a percentage of precipitation, was smallest at station 08123650; the period of record for that station, however, is 8 years less than the period of record for the other stations. The mean-annual runoff represents only 0.01 in. from the 1,505-mi^2 watershed upstream from station 08123650 and also represents much less than 1 percent of the approximately 21 in. of mean-annual precipitation estimated for the watershed from the gage at Big Spring. The greatest calculated runoff was in the intervening watershed just upstream from station 08120700 in northern Mitchell County. The mean-annual runoff was 2.22 in., about 10 percent of the mean-annual precipitation estimated for that area. These runoff data generally agree with the range of mean-annual runoff for the study area of about 0.2 in. for the western and southern parts of the area to about 1.5 in. for the extreme eastern part reported by Gebert and others (1987).

Most of the remaining precipitation was lost to evapotranspiration with lesser quantities infiltrating to shallow aquifers. Flat slopes throughout the area cause slow runoff velocities and allow for much surface storage of precipitation. Permeable soils throughout much of the area allow large quantities of infiltration to occur (Mount and others, 1967).

Relative inflow contributions to E.V. Spence Reservoir can be inferred from the data shown in figure 5. For this analysis, the small streams that flow directly into the reservoir were assumed to contribute only small quantities of runoff. These streams included only about 368 mi^2 compared to about 4,700 mi^2 of contributing drainage from the Colorado River. The data indicate that 31 percent of the inflow to the reservoir originated from Beals Creek upstream from station 08123800. An estimate of the contribution of the entire Beals Creek watershed was made by adding the estimated runoff for the ungaged part of the watershed downstream from the station, to that measured at the station. The unit runoff for the intervening watershed upstream from the station was assumed to represent the area downstream from the station. This calculation produced 31 ft^3/s as the mean runoff from the entire Beals Creek watershed, or about 35 percent of the contribution from the Colorado River to E.V. Spence Reservoir.

Data for station 08120700 indicate that 42 percent of the inflow to E.V. Spence Reservoir originated from the watershed upstream from that station. Little flow originated from Lake J.B. Thomas during the period of record. Since 1968, however, much of the low flow from that area has been diverted by the Colorado River Municipal Water District into an off-channel reservoir. Subsequently, the median streamflow at station 08121000 was much less than that at station 08120700 (fig. 5). Flood flows, however, constitute most of the total flow. The mean-annual streamflows for the two stations are comparable, indicating little effect of the diversion on total flow.

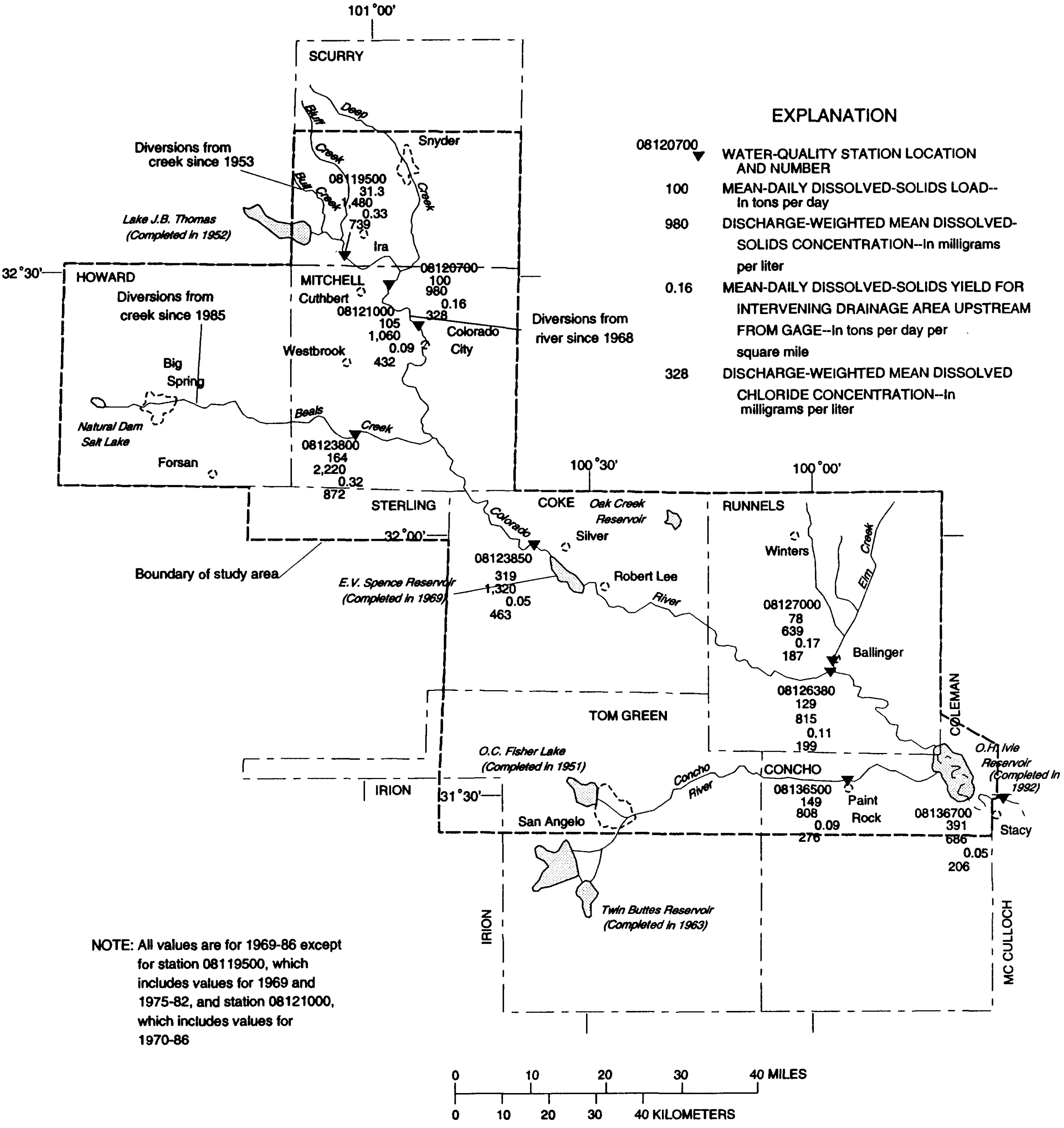
Analyses similar to those made for E.V. Spence Reservoir were made for contributions to O.H. Ivie Reservoir. Station 08136700, downstream from O.H. Ivie Reservoir, was used to estimate what the inflow to the reservoir would be after the reservoir was filled. The data shown in figure 5 indicate that only 4 percent of the flow to the reservoir came from the Colorado River upstream from station 08124000. About 96 percent of the flow at O.H. Ivie Reservoir was runoff from the watershed downstream from the dam at E.V. Spence Reservoir. About 21 percent of the flow to O.H. Ivie Reservoir was from Elm Creek.

The contribution of the Concho River to O.H. Ivie Reservoir was estimated by an analysis similar to that for Beals Creek. The unit runoff from the watershed between stations 08136000 and 08136500 (fig. 5) was applied to the ungaged watershed downstream from station 08136500. The mean-annual streamflow for the entire Concho River was calculated as 76 ft^3/s, or 36 percent of the total flow to O.H. Ivie Reservoir. The mean-annual streamflow at the Concho River at San Angelo station was 27.4 ft^3/s, or 36 percent of the total flow from the Concho River. The Colorado River, exclusive of Elm Creek and the Concho River, was assumed to contribute the remainder of the inflow to O.H. Ivie Reservoir--about 43 percent of total inflow.

Dissolved-Solids Concentrations and Loads

Data for the same period used to determine runoff characteristics, 1969-86, were used to determine dissolved-solids concentrations and loads for water at the seven stations for which water-quality data were collected during that period (fig. 6). Water-quality station 08119500 (1969, 1975-82) also was included to provide data for the Colorado River and its tributaries upstream from the confluence with Deep Creek. Station 08121000 (1970-86) also was included because of its importance in determining the effects of upstream diversions. Discharge-weighted mean concentrations were computed by multiplying the stream discharge for a sampling period by the concentrations of individual water-quality constituents for the same period, and dividing the sum of the products by the sum of the discharges. The largest discharge-weighted mean dissolved-solids concentration in the Colorado River was 1,480 mg/L at station 08119500.

The discharge-weighted mean dissolved-solids concentration for the Colorado River decreased from station 08119500 to station 08121000, indicating an inflow of water with smaller dissolved-solids concentrations between the two stations. Differences between periods of record at the two stations, however, preclude drawing definitive conclusions from these data. The mean concentration for water from station 08121000 to station 08123850 just upstream from E.V. Spence Reservoir increased substantially, from 1,060 to 1,320 mg/L, primarily because of inflow with a dissolved-solids concentration of 2,220 mg/L from Beals Creek. Downstream from E.V. Spence Reservoir, small discharge-weighted mean dissolved-solids concentrations from Elm Creek and the Concho River contributed to decreased concentrations (686 mg/L) in the Colorado



NOTE: All values are for 1969-86 except for station 08119500, which includes values for 1969 and 1975-82, and station 08121000, which includes values for 1970-86

Figure 6. Mean-daily dissolved-solids loads, discharge-weighted mean dissolved-solids concentrations, mean-daily dissolved-solids yields, and discharge-weighted mean chloride concentrations, 1969-86.

River at station 08136700 downstream from O.H. Ivie Reservoir.

The discharge-weighted mean dissolved-solids concentrations for water from all nine stations exceeded the SMCL of 500 mg/L for public-water supplies as established by the U.S. Environmental Protection Agency (1990a). Concentrations in water from the four stations downstream from E.V. Spence Reservoir did not exceed the maximum constituent level of 1,000 mg/L recommended by the Texas Department of Health (1988). Four of the five stations upstream from E.V. Spence Reservoir, however, had water with discharge-weighted mean dissolved-solids concentrations that exceeded 1,000 mg/L (fig. 6).

All five stations upstream from E.V. Spence Reservoir had discharge-weighted mean dissolved-chloride concentrations greater than the SMCL of 250 mg/L (U.S. Environmental Protection Agency, 1990a) and the secondary constituent level of 300 mg/L (Texas Department of Health, 1988). The two stations with water having the largest concentrations were 08123800 (872 mg/L) and 08119500 (739 mg/L). Discharge-weighted mean dissolved-chloride concentrations in water at stations downstream from E.V. Spence Reservoir did not exceed the level set by the TDH. Water from station 08136500, however, had a discharge-weighted mean dissolved-chloride concentration of 276 mg/L, which slightly exceeded the SMCL established by the USEPA.

Average dissolved-solids concentrations are represented by the median for each station (fig. 7). The median dissolved-solids concentration is much larger than the mean because the means are biased by large stream discharges associated with floods. Dissolved-solids concentrations during floods are much smaller than during base-flow conditions. Freshwater from flood runoff greatly dilutes the larger dissolved-solids concentrations from base flows.

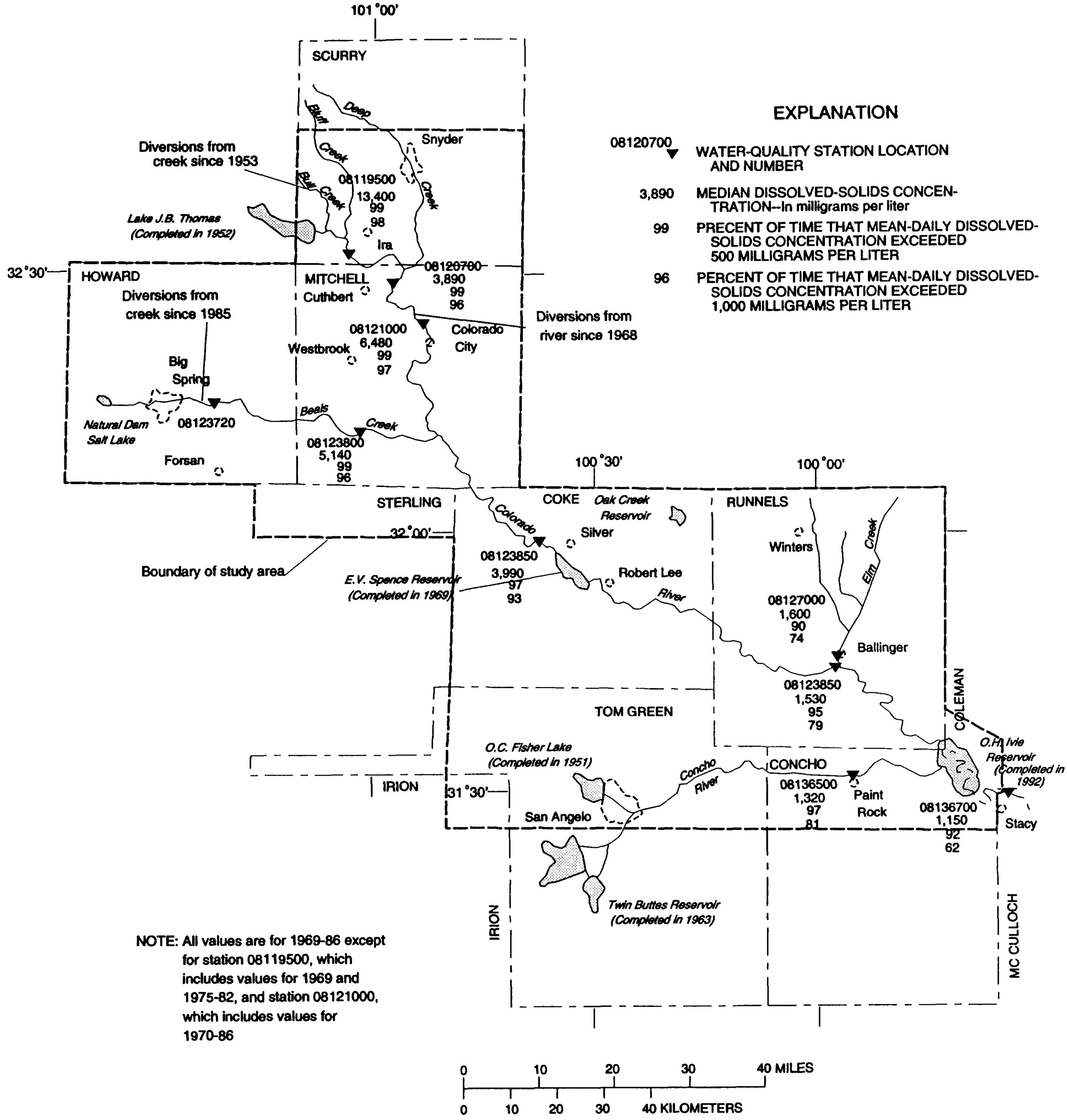
The median dissolved-solids concentration in water for each station (fig. 7) exceeded the MCL established by the USEPA (500 mg/L) and the level established by the TDH (1,000 mg/L). The mean-daily dissolved-solids concentration in water for each station exceeded the USEPA level at least 90 percent of the time during 1969-86. The TDH level was exceeded slightly less frequently for most of the stations.

Contributions of dissolved-solids loads from the gaged streams to E.V. Spence and O.H. Ivie Reservoirs can be inferred from figure 6. The estimated dissolved-solids load from the entire Beals Creek watershed, 186 ton/d, was obtained by multiplying the discharge-weighted mean dissolved-solids concentration (2,220 mg/L) by the estimated mean streamflow at the mouth of Beals Creek (31 ft^3/s) and by 0.0027, which converts the units to tons per day. This load represented 58 percent of the Colorado River's load contribution to E.V. Spence Reservoir. Beals Creek contributed only about 35 percent of the inflow to the reservoir; however, 58 percent of the dissolved-solids loads to the reservoir were from Beals Creek. The discharge-weighted mean dissolved-solids concentration (2,220 mg/L) from Beals Creek was more than double that for station 08121000 (1,060 mg/L) and accounted for the large load contribution to the reservoir. Loads from the small streams that inflow directly to the reservoir were not used for this analysis. The Colorado River, exclusive of Beals Creek, was assumed to contribute most of the remainder of the loads to E.V. Spence Reservoir--about 42 percent of the total.

Load contributions to O.H. Ivie Reservoir were calculated for Elm Creek, for the Concho River, and for the Colorado River exclusive of Elm Creek and the Concho River. Elm Creek contributed 20 percent of the load to the reservoir. On the basis of an analysis similar to that done for Beals Creek, the load contribution from the Concho River was 166 ton/d, or 42 percent of the load to the reservoir. The load from the Colorado River, exclusive of the two streams, therefore, was calculated as 38 percent of the total.

The mean-daily dissolved-solids yield was calculated as the difference between the load at a given station and the load at the station immediately upstream from the given station (fig. 6), divided by the contributing drainage area between the stations. This analysis allows for comparison of yield contributions from different watersheds.

The largest mean-daily dissolved-solids yields originated from the drainage area upstream from station 08119500 [0.33 $(ton/d)/mi^2$], and from the drainage area upstream from station 08123800 [0.32 $(ton/d)/mi^2$]. The yield contributions from these areas greatly exceeded that from the area with the next largest yield--0.17 $(ton/d)/mi^2$ from the drainage area upstream from station 08127000. The smallest yield, 0.05 $(ton/d)/mi^2$, originated from the Colorado River watershed just upstream from station 08123850 and from the watershed just upstream from station 08136700. For the yield computation for Beals Creek, the assumption was made that 94 percent of the load at station 08123800 originated from the watershed



NOTE: All values are for 1969-86 except for station 08119500, which includes values for 1969 and 1975-82, and station 08121000, which includes values for 1970-86

Figure 7. Median dissolved-solids concentrations and percentages of mean-daily dissolved-solids concentrations that exceeded 500 and 1,000 milligrams per liter, 1969-86.

east of Big Spring, because 94 percent of the flow originated from that watershed and dissolved-solids concentrations were comparable throughout the watershed. A similar assumption was made for the yield computation for station 08136500--60 percent of the flow at the station originated from the watershed east of San Angelo and, thus, 60 percent of the loads.

Gains and Losses of Streamflow

Stream discharge measurements made for this study in 1986 and 1987 on the Colorado River, Beals Creek, Elm Creek, and the Concho River provided data to estimate the gains and losses of streamflow to shallow aquifers and the salinity of the shallow-aquifer discharges to these streams. Discharges for the common period (1969-86) at the streamflow-gaging stations (fig. 5) were reviewed for flow changes following the measurements. The largest change in mean-daily flows was only a few percent, thus steady flow conditions were assumed throughout all four streams during the period when measurements were made. Streamflow and specific conductance were measured at each site in 1986 and 1987. Samples collected in 1987 also were analyzed for chloride concentrations.

The discharge measurements were made during late fall or winter, thus evapotranspiration losses in the streams were minimal compared to the gains from and losses to aquifers. Diversions from the streams also were minimal, except for the diversions near Big Spring and Colorado City, based on review of the permitted withdrawals from records at the TNRCC. The measurements were made after periods of at least 2 weeks without runoff-producing precipitation or release from reservoirs; thus, most of the sustained flows were from aquifer discharges to the streams. The difference in streamflow and changes in specific conductance between adjacent sites, therefore, are associated with recharge to or discharge from aquifers adjacent to the streamflow-study sites. The streamflow and water quality also are influenced by each tributary with flow; thus, tributaries were included in the computations of gains and losses.

The 1986 measurements were made during "dry" conditions when streamflows were small and shallow-aquifer levels were low. About 4 months of base-flow conditions preceded the 1986 measurements. Hydrologic conditions during the 1987 measurements, however, were considerably different. Although there was no runoff for a few weeks prior to the 1987 measurements, there was much runoff during the 6 months ending in October 1986. Annual precipitation in 1986, which exceeded 40 in. in some places, occurred mostly during May-October 1986, and resulted in the largest recorded runoff and the highest measured ground-water levels in the area. Consequently, aquifer discharges to streams during the 1987 measurements also would be large.

The gains and losses of flow for reaches on the main channel of the Colorado River, Beals Creek, Elm Creek, and the Concho River were calculated by the following equation:

$$Qg = Qd - Qu - Qt, \qquad (2)$$

where Qg = gain (positive) or loss (negative) in streamflow between adjacent sites;

Qd = streamflow at downstream site;

Qu = streamflow at upstream site; and

Qt = streamflow for all tributaries between upstream and downstream sites.

The specific conductance and chloride concentration in streamflow gain were calculated by the following equation:

$$Cg = (QdCd - QuCu - QtCt)/Qg, \qquad (3)$$

where Cg = specific conductance value or chloride concentration in ground-water discharge;

Cd = specific conductance value or chloride concentration in flow at downstream site;

Cu = specific conductance value or chloride concentration in flow at upstream site; and

Ct = specific conductance value or chloride concentration in tributary flow.

Specific conductance is a measure of the ability of water to conduct an electrical current and is related to the types and concentrations of ions in solution. The specific conductance of water increases linearly as the dissolved-solids concentration increases, and consequently was used to estimate the dissolved-solids concentrations in streamflow. Equations were developed for each water-quality station that had specific conductance and dissolved-solids data for the common period (1969-86). The equation developed for each station was used to estimate dissolved-solids concentrations for the 1986 and 1987 specific-conductance measurements from the river reach closest to the station.

Part of the gains or losses to shallow aquifers may be associated with alluvial and terrace deposits along almost the entire length of the Colorado River and its major tributaries in the study area. These deposits, which are along the lower reaches of most of the minor tributaries to major tributaries, range from about 0.2 to about 1.5 mi in width. Depths of the deposits can be large as indicated by the alluvial deposits in the eastern part of the study area, which are as much as 35 ft thick (University of Texas, Bureau of Economic Geology, 1976). The deposits, therefore, can be considered aquifers in places. Most shallow-aquifer discharge or recharge associated with the four streams is believed to pass through the deposits to or from other aquifers adjacent to the deposits. Some recharge to the other aquifers or discharge to the streams may originate from precipitation on the deposits. Floods also might contribute water to the deposits. Flood stages and widths of the streams during floods, however, probably are not sufficient to allow much water movement to the deposits from this source. Also, the duration of floods is short, usually a few days or less; therefore, little water from floods moves to the deposits.

Colorado River

Streamflow, gains and losses of streamflow (calculated using equation 2), and estimated dissolved-solids concentrations of streamflow gains at sites sampled in 1986 and 1987 for each reach of the Colorado River are shown in figure 8. Relative accuracies of the gains and losses can be inferred from the streamflow; increases in errors can occur with increases in streamflow. The stream discharges are subject to errors of as much as 5 to 8 percent of the measured flow, thus the accuracy of each gain or loss is subject to error of similar magnitude. Similar type errors are probable for the concentration of each water-quality constituent for each gain. The flow gain is the denominator of the equation used to estimate the water-quality constituent for the gain (equation 3); therefore, the potential error for each water-quality constituent also increases as the gain becomes a larger part of the measured flow. Most reaches of the Colorado River had streamflow gains, and the gains were considerably larger for the 1987 measurements than for the 1986 measurements (fig. 8). Some reaches had no flow in 1986.

The estimated dissolved-solids concentrations of the streamflow gains generally decrease in downstream direction. As expected, the estimated dissolved-solids concentrations of the gains generally were smaller for the 1987 measurements presumably because the larger gains from that set of measurements contained freshwater from recent precipitation that diluted the larger dissolved-solids concentrations of the aquifer discharge. The largest estimated dissolved-solids concentrations of gains were upstream from E.V. Spence Reservoir, in the upstream-most reaches.

Throughout most of the reaches in the river, the estimated dissolved-solids concentrations of the streamflow gains exceeded the concentrations in surface runoff. This is shown by comparing the estimated dissolved-solids concentrations of the gains (fig. 8) with the discharge-weighted mean (fig. 6) and median dissolved-solids concentrations (fig. 7) at nearby water-quality stations. The median dissolved-solids concentration of 13,400 mg/L for station 08119500 was comparable to that of the gains in that area because releases seldom have been made from Lake J.B. Thomas. Thus, there was little runoff at that station. Also, runoff from precipitation in the small watershed at this station was only for short durations, resulting in low flows (aquifer discharge) most of the time. Dissolved-solids concentrations for station 08121000 were approximately similar to those estimated for gains between river miles 210 and 197 because of diversions from the river just upstream from the station.

Beals Creek, Elm Creek, and the Concho River

Gains and losses of streamflow for Beals Creek, Elm Creek, and the Concho River are shown in figure 9. These streams had large gains or only small losses throughout most reaches. Most streamflow gains computed from the 1987 measurements were larger than those for the 1986 measurements.

The estimated dissolved-solids concentrations of the streamflow gains along the main channels of the three streams are shown in figure 10. Beals Creek has the largest estimated dissolved-solids concentrations of streamflow gains. The concentrations range from about 6,000 to more than 12,000 mg/L, which is comparable to the estimated concentrations of gains in the reaches of the Colorado River upstream from E.V. Spence Reservoir (fig. 8). Estimated dissolved-solids concentrations of gains in Elm Creek were less than 2,000 mg/L throughout the length of the stream. Estimated dissolved-solids concentrations of gains in the Concho River ranged from about 1,600 to about 2,200 mg/L.

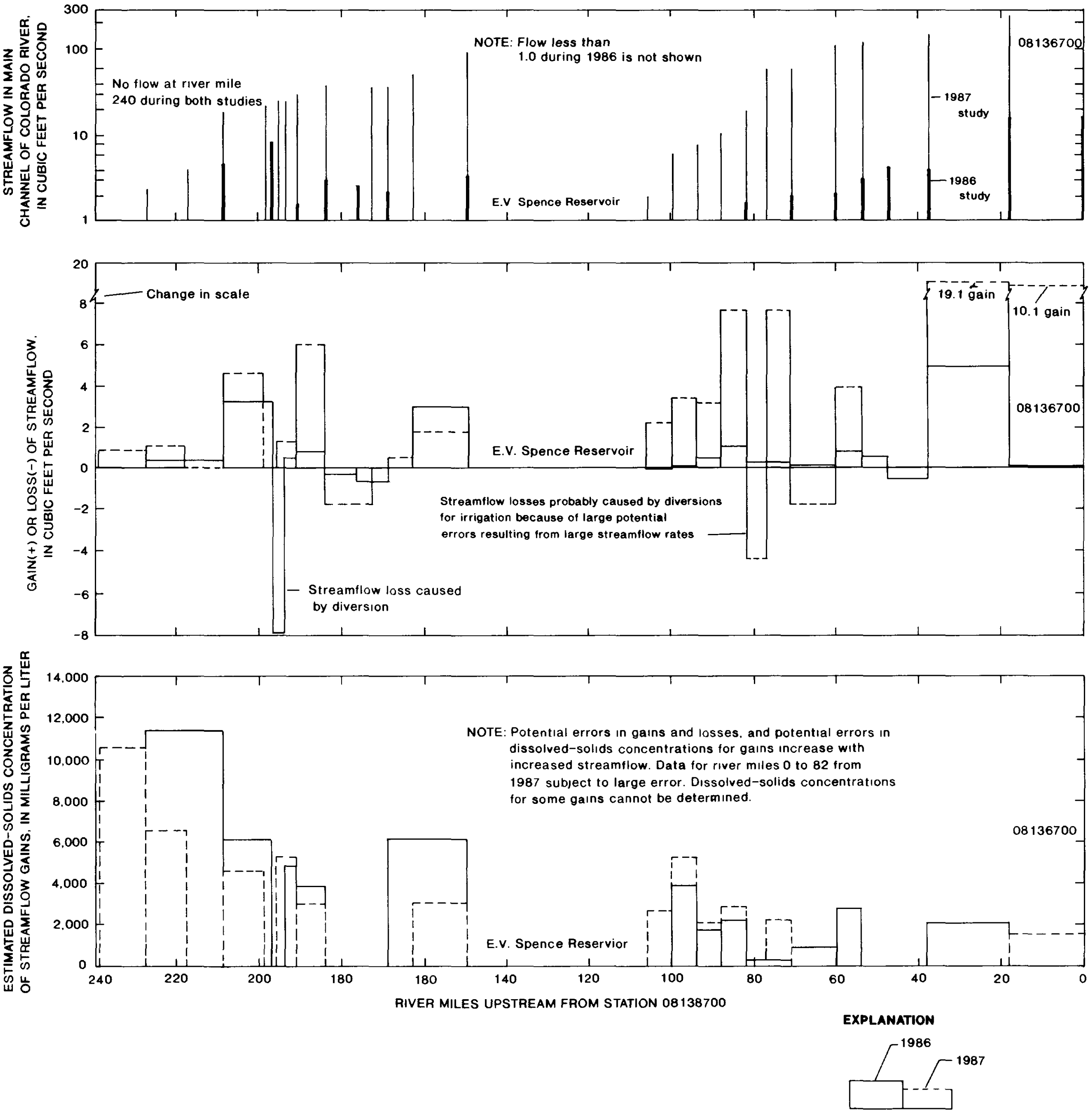


Figure 8. Gains and losses of streamflow and estimated dissolved-solids concentrations of streamflow gains along the main channel of the upper Colorado River, Texas, 1986 and 1987.

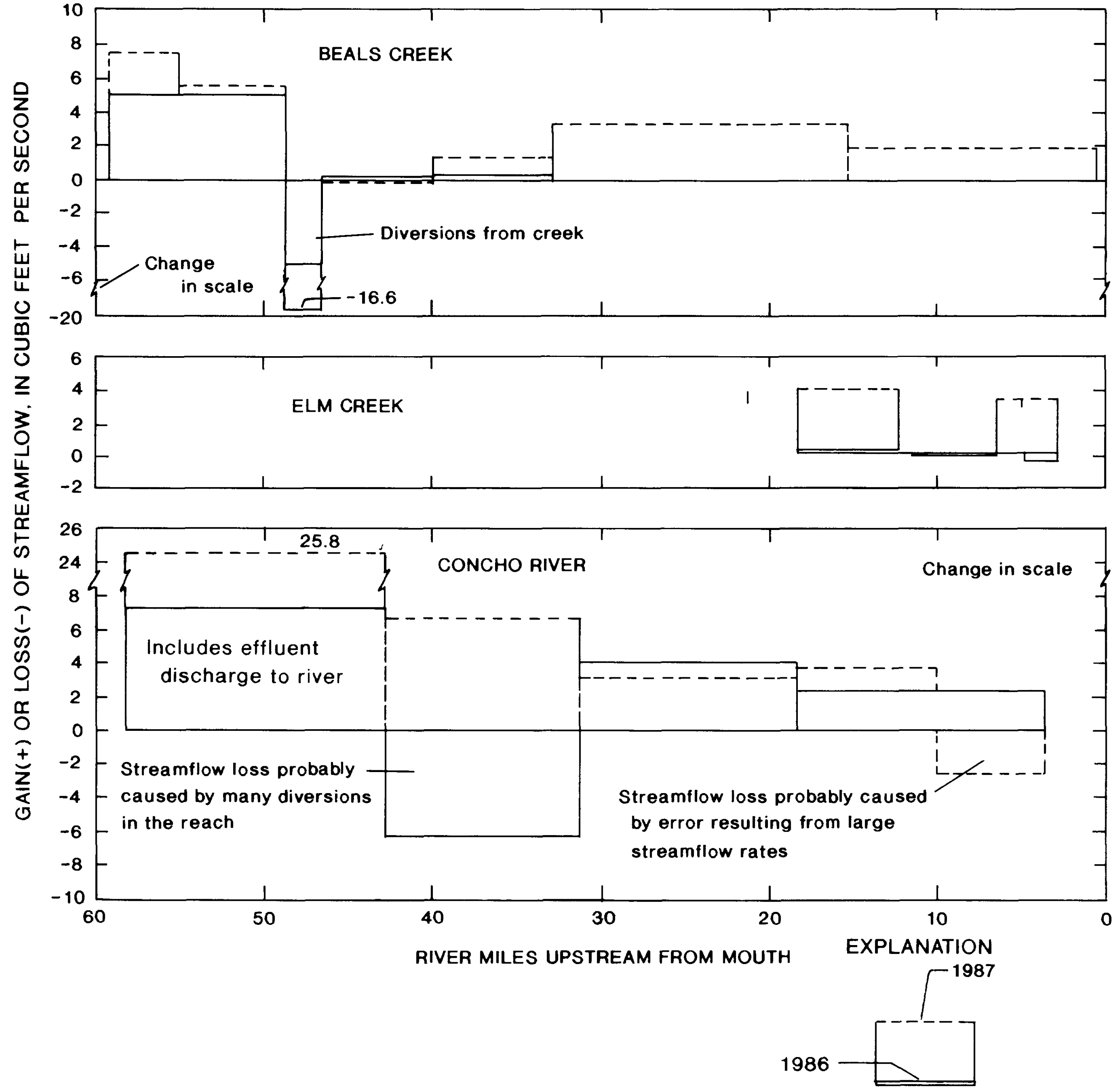
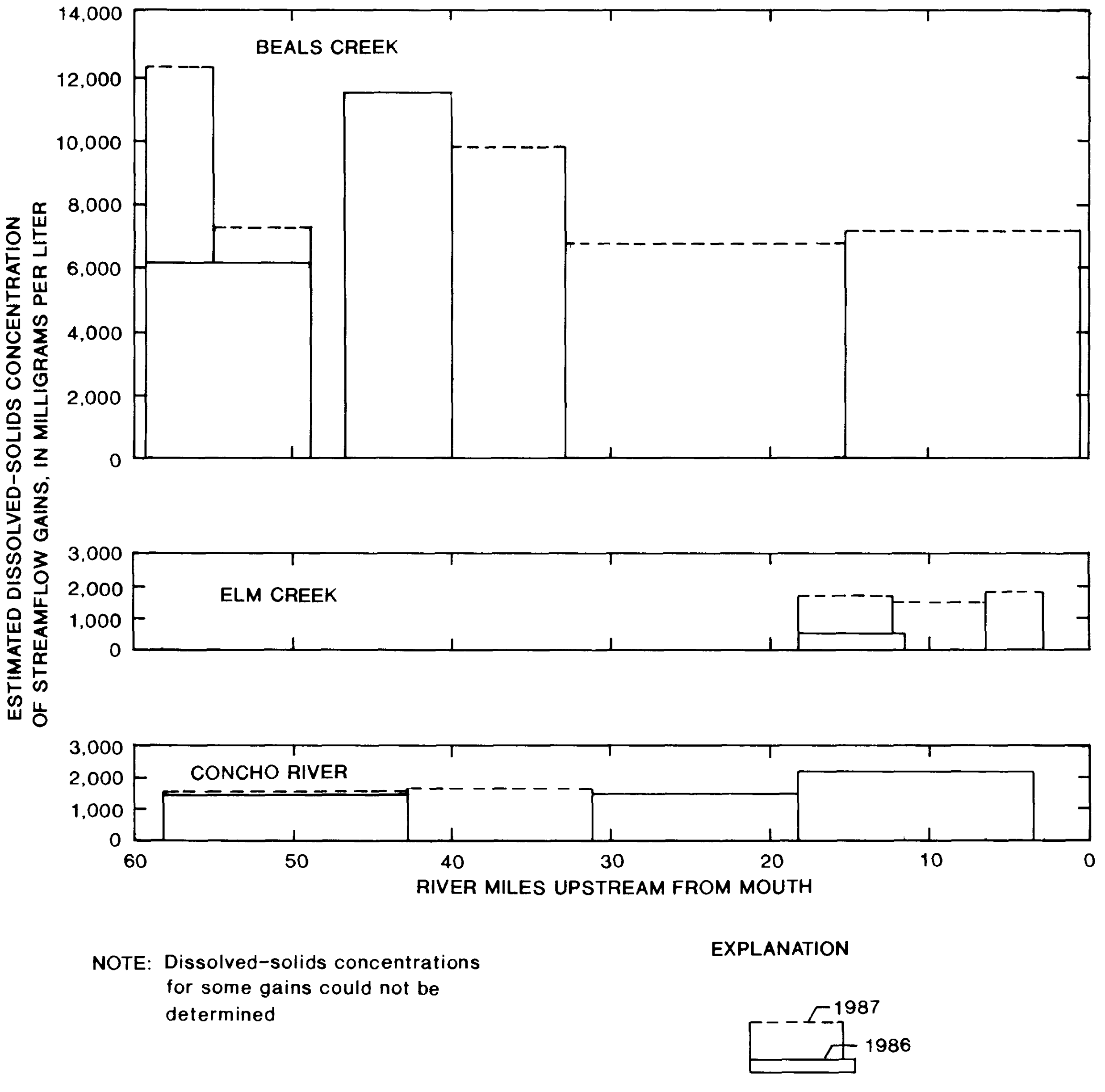


Figure 9. Gains and losses of streamflow along the main channels of Beals Creek, Elm Creek, and the Concho River, Texas, 1986 and 1987.



NOTE: Dissolved-solids concentrations for some gains could not be determined

Figure 10. Estimated dissolved-solids concentrations of streamflow gains along the main channels of Beals Creek, Elm Creek, and the Concho River, Texas, 1986 and 1987.

The estimated dissolved-solids concentrations of streamflow gains along Beals Creek, Elm Creek, and the Concho River (fig. 10) were larger than the discharge-weighted mean and median dissolved-solids concentrations of runoff at nearby streamflow stations (figs. 6 and 7). For example, the estimated dissolved-solids concentrations of gains on every reach of Beals Creek exceeded the discharge-weighted mean and median dissolved-solids concentrations of runoff from 1969-86 at station 08123800. The estimated dissolved-solids concentrations of aquifer discharges to Beals Creek, therefore, were larger than those of runoff, with the largest concentrations in the upper reaches. The estimated dissolved-solids concentrations of most streamflow gains in Elm Creek and the Concho River were only slightly larger than median concentrations at the respective stations. Consequently, the estimated dissolved-solids concentrations of aquifer discharges were only slightly larger than dissolved-solids concentrations of runoff for the two streams.

Salinity of Streamflow

Historical Changes in Salinity

Many studies on the quality of streamflow in the study area have been made since 1946. Most of these studies were directed toward determining the sources of dissolved solids. Two such studies by the USGS were of the quality of streamflow in the Bull Creek area of Scurry County in 1946 and in the Cuthbert area of Mitchell County in 1948 (McDowell, 1959). Reed (1961) presented evidence that brines in the Colorado River between Lake J.B. Thomas and Colorado City are related directly to oil-field activity. Rawson (1973) concluded that salinity in the Colorado River between Lake J.B. Thomas and E.V. Spence Reservoir probably resulted from oil-field brines and from saline water not related to oil-field activities. The U.S. Army Corps of Engineers (1974) concluded that salinity in the river was from natural sources and oil-field activity with most of the evidence indicating oil-field activity as the principal contributor.

Historical data on the specific conductance and concentration of dissolved solids in streamflow were compared with recent data to determine changes in water quality. Temporal changes and areal variations in specific-conductance values and dissolved-solids concentrations can provide circumstantial information on the source of salinity in streamflow. However, temporal changes or trends are difficult to identify because dissolved-solids concentrations fluctuate with changes in hydrologic conditions.

Temporal trends for annual-maximum dissolved-solids concentrations at stations with long-term daily values of specific conductance were examined. The annual-maximum dissolved-solids concentrations were estimated for each station on the basis of the mathematical relations between daily specific conductance and dissolved-solids concentrations. A statistical summary of the estimated annual-maximum dissolved-solids concentrations prior to and after 1973 is presented in the following table:

Station and period of record	Range in estimated annual-maximum dissolved-solids concentrations (thousands of milligrams per liter)			
	Prior to 1973		Beginning 1973	
	Mean	Range	Mean	Range
08119500 (1959-70, 1975-82)	48	38-60	27	17-41
08120700 (1965-87)	30	10-48	5.5	4.3-11
08121000 (1947-68, 1970-87)	23	11-46	13	5.2-24
08123800 (1959-87)	9.6	5.1-15	11	7.5-14
08123850 (1957-87)	9.7	6.5-16	8.0	6.3-11
08126380 (1961-87)	3.4	1.9-9.4	2.6	1.7-5.2
08127000 (1968-87)	2.4	2.3-2.5	1.8	1.6-2.4
08136500 (1968-87)	1.7	1.4-1.8	1.6	1.4-2.1
08136700 (1968-87)	1.9	1.6-2.2	1.9	1.4-3.3

Data for seven of the nine stations indicated that mean estimated annual-maximum dissolved-solids concentrations were lower from 1973 to 1987 than prior to 1973, although differences between periods of record preclude drawing any definitive conclusions. The differences generally decreased from upstream to downstream stations. The exceptions were differences for station 08123800 (Beals Creek), which indicated a slight increase after 1973, and station 08136700 downstream from O.H. Ivie Reservoir, which indicated no change.

Double-mass curves of cumulative annual-mean discharge and calculated dissolved-solids loads were plotted for each of the nine water-quality stations in the study area, using long-term daily values for each station and data collected in 1987 and 1988. Straight-line segments were drawn visually to best fit the plot of the cumulative values. The mean dissolved-solids load per unit of streamflow was calculated for each of the line segments. Results are summarized in the following table:

Station	Period and associated ratio of dissolved-solids discharge to streamflow [(ton per day) per (cubic foot per second)]
08119500	1962-69 (8.8); 1975-82 (3.6)
08120700	1966-78 (3.4); 1981-86 (2.6); 1987-88 (3.7)
08121000	1965-68 (3.9); 1970-86 (2.9); 1987-88 (4.6)
08123800	1959-65 (1.6); 1966-74 (4.2); 1975-85 (6.1); 1986 (8.3); 1987-88 (21.4)
08123850	1958-65 (2.3); 1966-85 (3.4); 1986 (4.7); 1987 (11.5); 1988 (15.0)
08126380	1965-77 (2.1); 1978-85 (1.5); 1986 (3.4); 1987 (5.8); 1988 (10.8)
08127000	1968-75 (2.2); 1976-86 (1.2); 1987-88 (2.4)
08136500	1968-86 (2.2); 1987 (2.6); 1988 (3.3)
08136700	1969-77 (2.0); 1978-85 (1.6); 1986 (2.2); 1987 (3.2); 1988 (6.7)

Excluding the 1986-88 data, evaluations of temporal trends in dissolved-solids loads from double-mass analysis were not conclusive because smaller unit loads typically are present in larger flows; wetter years produce runoff with more freshwater; timing and quantity of runoff will influence the salinity of that water; and the data fitted to a line segment are arbitrary.

Dissolved-solids loads increased between 1986 and 1987-88 at all stations with data for those years. The increases in the dissolved-solids loads at the stations may be caused partly by flushing of salt deposits in remote parts of watersheds to receiving streams--deposits that may be affected only by large amounts of surface runoff. The large amount of surface runoff occurred because the 1986 precipitation is the largest recorded annual precipitation for 6 of the 11 rain-gage sites in the study area as of 1988 (fig. 5), and the remaining gages had near-record precipitation that year. Precipitation in 1987 was greater than normal for all but one of the gages.

Some of the increases between 1986 and 1987-88 in dissolved-solids loads are attributed to site-specific occurrences. For example, diversions of low flow upstream from station 08121000 and from Beals Creek just east of Big Spring (fig. 5) were limited during 1986-87 because the reservoirs that receive diversions were full during much of that time (J.R. Lewis, Colorado River Municipal Water District, oral commun., 1989). Thus, much of the low flows with large dissolved-solids concentrations could not be diverted from these streams, resulting in increased dissolved-solids concentrations in base runoff at downstream gaging stations.

On the basis of streamflow and dissolved-solids data for Beals Creek, about 61,000 acre-ft of water from Natural Dam Salt Lake flowed to the lower reaches of Beals Creek between September 1986 and August 1988 (J.R. Lewis, Colorado River Municipal Water District, written commun., 1989). Prior to 1986, there had been no known discharge from Natural Dam Salt Lake, except for evapotranspiration, since at least the 1950's (O.H. Ivie, Colorado River Municipal Water District, oral commun., 1989). Large amounts of surface runoff during 1986-87 caused the lake to fill to structurally hazardous levels and necessitated the releases. The outflow contained about 654,000 tons of dissolved solids, thus the mean dissolved-solids concentration of that water was 7,900 mg/L--considerably larger than the long-term mean of 2,220 mg/L for runoff at station 08123800 (fig. 6).

From September 1986 to August 1988, the dissolved-solids load at station 08123850 was about 1.28 million tons. The releases from Natural Dam Salt Lake, therefore, represented about 51 percent of the dissolved-solids load to E.V. Spence Reservoir from September 1986 to August 1988. About 214,000 acre-ft of water containing 934,000 tons of dissolved solids was released from E.V. Spence Reservoir during this time; thus, the downstream reaches of the Colorado River received much of the inflow loads to the reservoir. The mean dissolved-solids concentration of the water in these releases was 3,200 mg/L--considerably larger than the mean of 815 mg/L for station 08126380 (fig. 6). During fall 1988, the Colorado River Municipal Water District increased the storage capacity of Natural Dam Salt Lake to insure that future releases from the lake would not be necessary (J.R. Lewis, Colorado River Municipal Water District, written commun., 1989).

An evaluation of temporal trends for 1973-82 data in the runoff quality for stations in the Colorado River Basin was made by Andrews and Schertz (1986). The Seasonal Kendall Test was used to remove the effects of streamflow and seasonal changes on water quality. Data for three stations show large annual increases in dissolved-solids concentrations: 08121000 (270.6 mg/L); 08123800 (277.8 mg/L); and 08123850 (166.7 mg/L). These trends represent increases of 4, 5, and 4 percent per year, respectively, for the 10-year period.

Comparison of changes in dissolved-solids concentrations at selected gaging stations between results of this study and results presented by Andrews and Schertz (1986) indicated that the concentration of dissolved solids (1) generally decreased in Elm Creek and in the Colorado River upstream from Beals Creek; (2) increased in Beals Creek; and (3) did not change in the Concho River. Results for the Colorado River below Beals Creek were inconclusive. Differences in results between this study and the study reported by Andrews and Schertz (1986) were attributed primarily to differences in the way changes were computed and in the periods of measurement.

Principal Sources of Dissolved Solids

The principal source of dissolved solids in five of nine streamflow samples, classified by salt-norm analysis, was from the dissolution of sulfur-bearing minerals (fig. 11, table 3 at end of report). All five samples were from tributaries of the Colorado River. Salt norms from the five samples were composed principally of some combination of anhydrite, alkali, and magnesium sulfate normative minerals. Among these five samples, only the Jayhawk Creek sample (pl. 1) was near saturation with respect to gypsum (fig. 12). Jayhawk Creek crosses outcrops of formations in the Whitehorse-San Andres aquifer and may receive discharges of gypsum dissolution-modified water from the aquifer. Two of the five samples, from Canyon Creek and Coyote Creek, had percentages of normative halite of 42.1 and 39.2, respectively (table 3). The data indicate a substantial contribution of chloride to these two samples from mixing with deep-aquifer brine or from the dissolution of evaporite deposits in the adjacent alluvium.

Four of the nine streamflow samples (fig. 11) were classified by salt-norm analysis as similar in chemistry to halite dissolution brine or a mixture of deep-aquifer brine and less-saline water (sites on Bull Creek, Bluff Creek, Colorado River, and Elbow Creek). Salt norms for each of the four samples contained normative halite in proportions greater than 45 percent (table 3). The samples from Colorado River and Elbow Creek each contained more than 1,000 mg/L of chloride (table 1). Water from Elbow Creek was classified using Br/Cl ratios as having, as a source of chloride, water from the Permian System deep aquifers. The Elbow Creek sampling site is downstream from the Moore oil field (table 4 at end of report). The Moore oil field produces some petroleum from the Permian System Wolfcamp aquifer.

The Br/Cl ratio of the sample from the Colorado River indicates that the source of chloride was from halite dissolution (table 4). The halite in the adjacent river alluvium was associated with migration of seepage from brine-disposal pits to the river and subsequent precipitation at the capillary fringe by evaporation from a shallow water table (Reed, 1961; Mount and others, 1967). Some of the salinity in water from the Colorado River, therefore, was affected by prior brine disposal.

Effects of Diversions

Since 1968, the loads and concentrations of the dissolved chemical constituents at station 08121000 (fig. 6) have been affected greatly by diversions from the river, beginning in late 1968, by the Colorado River Municipal Water District. The diversions are used by oil-field operators for water flooding and pressure maintenance of oil-bearing formations in the area. The maximum capacity of the pumps used to withdraw the water is about 100 ft^3/s ; actual withdrawals, however, usually are much less. Diversion ceases when the dissolved chloride concentration of the river decreases to less than about 500 mg/L (O.H. Ivie, Colorado River Municipal Water District, oral commun., 1988). Chloride concentrations in flood flows usually are less than 500 mg/L and commonly are sustained for a few days after storms.

The effect of these diversions on the dissolved-solids loads in the river was estimated by comparing the dissolved-solids loads at the stations immediately upstream and downstream from the diversion site for periods before and after the diversions began. Station 08120700 (fig. 6) is about 8 river mi upstream from the diversion site, and station 08121000 is about 2 mi downstream. For water years 1966-68 (October 1965 - September 1968), the common period of record prior to the beginning of diversions, the annual dissolved-solids loads for station 08121000 were 36, 21, and 26 percent larger, respectively, than the loads at station 08120700. The mean-daily loads at stations 08120700 and 08121000 were 103 and 132 ton/d respectively;

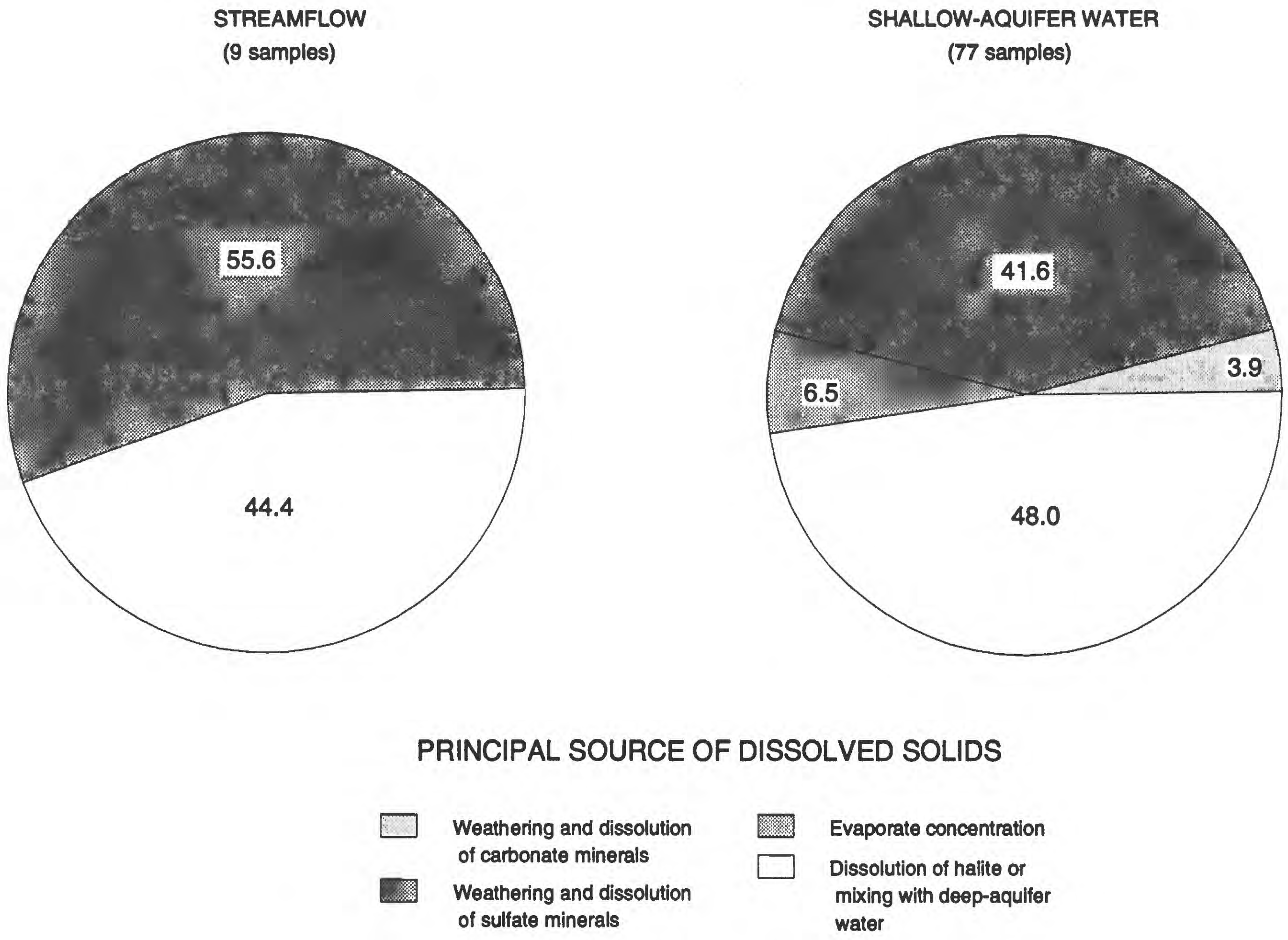


Figure 11. Principal sources of dissolved solids, in percent, for streamflow and shallow-aquifer water samples classified using salt-norm analysis. (Data from table 3 at end of report.)

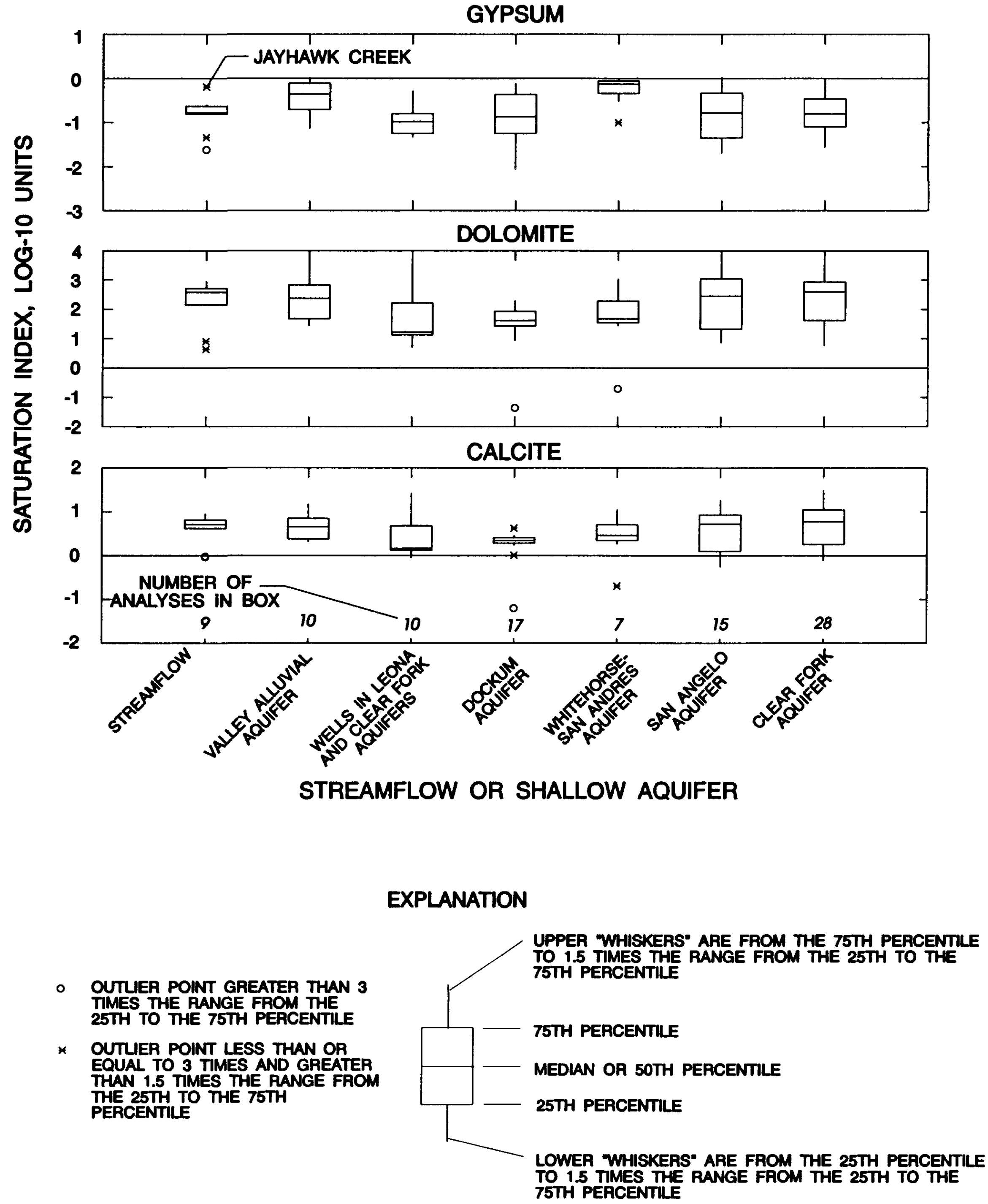


Figure 12. Boxplots showing mineral-saturation indices for water samples from streamflow and shallow aquifers in the upper Colorado River Basin, Texas.

thus the total load for the period at the downstream station exceeded the load at the upstream station by 28 percent. This increase was projected to be the expected increase contributed from the drainage area between the two stations.

Since 1968, however, the load at station 08121000 usually has been less than or comparable to the load at station 08120700. The common period of record (1969-86) was used to compare loads at the two stations after diversions began. The mean-daily dissolved-solids discharge for the common period of 1969-86 was 100 ton/d at station 08120700 and 105 ton/d at station 08121000. A 28-percent increase, 28 ton/d, would be the expected increase in discharge at the downstream station if the diversions did not exist. The actual discharge increase is 5 ton/d. Therefore, the diversion has removed dissolved-solids discharges averaging 23 ton/d since 1968. This decrease represents a 7-percent reduction in the mean-daily dissolved-solids loads to E.V. Spence Reservoir from the Colorado River (fig. 6), with a corresponding reduction of only about 3 percent of streamflow (fig. 5).

The mean (fig. 6) and median (fig. 7) dissolved-solids concentrations increased from station 08120700 to station 08121000 because diversions of most base flows cause extremely small streamflow most of the time at station 08121000. The small streamflow between the two stations is mostly ground-water discharges with dissolved-solids concentrations larger than concentrations in base runoff. The loads at the downstream station decreased, however, because large quantities of total flows were removed by diversion.

The effect of the diversion from Beals Creek, which began in 1985, on the loads to that stream could not be calculated directly because the quantity and quality data for streamflow or diversion flows were not available. An estimate of the potential load removal from the Beals Creek site by diversion was made by comparing streamflow and dissolved-solids characteristics with those for the Colorado River diversion site. The characteristics for streamflow below the Beals Creek diversion site were determined from station 08123720 (fig. 7). The station, installed in 1983, is only about 1 mi downstream from the site. Diversions from this site began near the end of 1985, thus only three common years, 1983-85, are available to compare streamflow and dissolved-solids characteristics that were not affected by diversions.

Median streamflows for stations 08120700 and 08123720 are similar for 1983-85, as are the low and medium mean flows. The diversions, estimated at about 10 ft^3/s were exceeded about 20 percent of the time at station 08120700 and about 10 percent of the time at station 08123720. The mean streamflow for station 08120700 is almost triple the mean streamflow at station 08123720 because of larger floods on the Colorado River; therefore, more flow is available from the Colorado River diversion than from the Beals Creek diversion.

The median dissolved-solids concentrations at stations 08120700 and 08123720 were 2,520 and 6,250 mg/L, respectively, for 1983-85. The dissolved-solids concentrations at the Beals Creek diversion frequently were double or even triple the concentrations at the Colorado River diversion. Although flows at the Colorado River diversion may have been double or triple those at the Beals Creek diversion, the dissolved-solids concentrations at the Colorado River diversion were about one-half to one-third of that at the Beals Creek diversion. The dissolved-solids discharge is the product of the streamflow and the dissolved-solids concentration. Therefore, the dissolved-solids discharge being removed from Beals Creek may have been comparable to the dissolved-solids discharge being removed from the Colorado River.

CHARACTERISTICS OF AQUIFERS

Throughout most of the study area, the formations that crop out contain water suitable for most domestic, agricultural, industrial, and municipal uses. These formations (shallow aquifers) yield freshwater or slightly saline water to most wells. Most formations below the exposed formations (deep aquifers) contain moderately saline to brine water.

Many ground-water studies, listed in the selected references, have been made in the study area during the last 60 years. Most of these studies were done on the basis of counties or on the basis of aquifers or specific areas. The U.S. Army Corps of Engineers (1980) concluded from a 5-year study of the Colorado River between Lake J.B. Thomas and Colorado City that the inflow of highly mineralized ground water contributes to the salinity of the river, but the source of the mineralized ground water was not determined. The study also documented many site cases of saline-water contamination of the ground water and streams as a result of oil-field activities. Rawson and others (1974) presented the water-quality characteristics for the Colorado River Basin. Rawson (1982) identified dissolved solids in the Colorado River by subreaches and concluded from trends in dissolved solids in the river that some part of the salinity is from oil-field brines, but most is of natural origin.

Geologic Framework

Outcrops of the geologic formations in the study area are shown on plate 2. The formations generally dip to the west (Mount, and others, 1967). Many formations from five geologic systems crop out in the area. The lithologies of units of these systems, which include limestones, shales, sands, and clays, are diverse.

The present-day geology represents the various depositional phases and environments through geologic time. During the Quaternary Period, thick sequences of sand and clay were deposited in the beds of the Colorado River and the lower reaches of most of its tributaries. The width of these deposits ranges from about 0.2 to about 1.5 mi and therefore are not wide enough to be shown in some places on plate 2. More detailed information on the surface geology in the study area is available from maps published by the University of Texas, Bureau of Economic Geology (1974, 1975, and 1976).

Shallow Aquifers

Shallow aquifers surveyed for this study are water-bearing formations whose production in the study area is for purposes other than oil- and gas-related activities. These aquifers, in descending order, are: (1) The Valley alluvial aquifer; (2) the Leona aquifer; (3) the High Plains aquifer; (4) the Dockum aquifer; (5) the Whitehorse-San Andres aquifer; (6) the San Angelo aquifer; and (7) the Clear Fork aquifer.

The hydrogeologic framework of shallow aquifers in the study area was described by Mount and others (1967). Detailed hydrogeologic interpretations were made for: Coke County (Wilson, 1973); Mitchell County (Shamburger, 1967); and Tom Green County (Lee, 1986) with some refinement by Dutton and others (1989) in Tom Green County. Generalized hydrogeologic interpretations also were made for the following parts of the study area: The part of the High Plains aquifer in Howard County (Nativ, 1988); the part of the Dockum aquifer in Howard, Mitchell, and Scurry Counties (Dutton and Simpkins, 1986); and Runnels County (Heil, 1972, and Kreitler, 1972).

The Valley alluvial aquifer is composed of Holocene and Pleistocene Series deposits associated with stream valleys and includes the water-yielding "alluvium" described by Mount and others (1967). In this report, the Valley alluvial aquifer is considered hydraulically connected to underlying formations. For example, water-table maps by Reed (1961) indicate that ground water from the Dockum aquifer discharges to parts of the Valley alluvial aquifer adjacent to the Colorado River. Other aquifers that probably share such a connection with the Valley alluvial aquifer near streams are the High Plains, Whitehorse-San Andres, and the Clear Fork.

The Leona aquifer is present in Tom Green County, western Concho County, and southwestern Runnels County. The Leona aquifer is hydraulically connected to the San Angelo and Clear Fork aquifers in the Concho River valley west of the city of San Angelo (Lee, 1986). The High Plains aquifer consists entirely of rocks of the Ogallala Formation in approximately the western one-half of Howard County (Nativ, 1988). The Dockum aquifer consists of permeable sediments of the Dockum Group and is designated by Dutton and Simpkins (1986) and by Core Laboratories, Inc., (1972a) as the "Triassic aquifer."

The Whitehorse-San Andres aquifer includes aquifers previously defined as the "Upper Guadalupe aquifer and the San Andres aquifer" (Core Laboratories, Inc., 1972a). This aquifer includes rocks of the Ochoa Series, formations of the Whitehorse Group, and the Blaine Gypsum of the Pease River Group. These water-yielding units are grouped together because of their similar lithologies and water-yielding characteristics. The San Angelo aquifer consists of the San Angelo Sandstone of the Pease River Group. The San Angelo aquifer is distinguished from the Whitehorse-San Andres aquifer by the relative lack of gypsum and evaporite deposits within the San Angelo and their greater quantity in the Whitehorse-San Andres aquifer.

The Clear Fork aquifer consists of water-yielding formations of the Clear Fork Group and the Lueders Limestone of the Wichita Group. The Arroyo Formation, the lowermost water-yielding formation in the Clear Fork aquifer, contains some gypsum in lenses and beds. The Lueders Limestone is similar in lithology and water-bearing characteristics to most formations in the Clear Fork Group and is stratigraphically adjacent to the Arroyo Formation. The Lueders Limestone, therefore, is included in the Clear Fork aquifer in the subsequent discussion.

The Whitehorse-San Andres, San Angelo, and Clear Fork aquifers contain saline water and, in places, oil and gas at depth. Therefore, they also are included in the deep-aquifer classification.

Wells and springs in the study area were inventoried in 1986 (U.S. Geological Survey, unpublished data). Where possible, the water level and specific conductance were measured at each site, and selected characteristics were determined. The inventory included as many sites as possible that had historical data so that trends in dissolved-solids concentrations could be observed for the longest period of record. Prior to the inventory, a list of sites with historical dissolved-solids concentrations was compiled from 24 ground-water reports, listed in the selected references, that include the study area, and from the computer files of the TWODB that contain ground-water data.

Most of the inventoried wells and springs are within about 10 mi of the reaches of the Colorado River, Beals Creek, Elm Creek, or the Concho River (pl. 3). Shallow-aquifer conditions close to the major streams were inventoried because base streamflows are made up of shallow-aquifer discharges. Most of the well and spring sites with historical data that were inventoried have site characteristics presented in one or more of the many ground-water reports on the area (Samuell, 1937; Samuell and Davis, 1938; George and Dalgarn, 1942; Rayner, 1959; and Knowles, 1964). The characteristics for other well and spring sites were determined from information provided by land owners and data from USGS quadrangle maps (1:24,000). The water-bearing units for most of the wells not inventoried prior to 1986 were determined from surface-geology maps published by the University of Texas, Bureau of Economic Geology (1974, 1975, and 1976).

Water Levels

Water-level altitudes (pl. 3) indicate that water movement is toward the major streams, which concurs with results from streamflow studies that ground water discharges to the major stream channels throughout most of the study area. Gradients of water levels are similar to gradients of surface topography. Therefore, most shallow aquifers in the upper Colorado River watershed were assumed to be recharged by runoff in the drainage area. The depths to water were shallow near the major streams and increased at greater distances from streams (pl. 4). Depths to water in most wells were less than 100 ft, but water levels were within 10 ft of the surface in some wells in Howard, Mitchell, and Runnels Counties. Lateral continuity for the water levels existed for adjacent formations that crop out, thus, water was assumed to move laterally between adjacent formations.

Hydrographs of water levels for selected observation wells (fig. 13) indicated that water levels during 1986 and 1987 were among the highest on record. The high levels are assumed to be the result of near-record 1986 annual precipitation. Water-level fluctuations for most wells were small--less than 15 ft--which was indicative of the water-table conditions throughout the area.

Salinity of Ground Water

Specific conductance was measured and water samples collected in 1986 from about 380 wells and 6 springs shown on plate 5. Water samples also were collected in 1987 from 42 wells and 1 spring that had water with specific conductances larger than 4,000 μS/cm during the 1986 inventory. Of the 42 wells that had water with specific conductances exceeding 4,000 μS/cm, 6 were unavailable during the 1987 inventory. Thus, six additional wells having water with specific conductances exceeding 3,000 μS/cm were arbitrarily selected and sampled to replace those wells. All samples collected in 1987 were analyzed for alkalinity, dissolved solids, eight major inorganic-chemical constituents identified earlier plus bromide, boron, and total organic carbon (table 1). Specific conductance also was measured in 1989 in water from some of the wells and from the spring.

The 1986 dissolved-solids concentration for each well and spring was estimated from the 1986 specific-conductance measurements on the basis of the mean ratio of the dissolved-solids concentration to the specific conductance for the data collected during 1987. The mean specific conductance for the wells and springs sampled during 1986 was 2,380 μS/cm--comparable to about 1,750 mg/L for the estimated mean dissolved-solids concentration. About 233 of the wells and springs had water with specific-conductance values larger than 1,400 μS/cm, which is comparable to an estimated dissolved-solids concentration larger than about 1,000 mg/L. Thus, about 60 percent of the wells and springs yielded water in 1986 that exceeded the

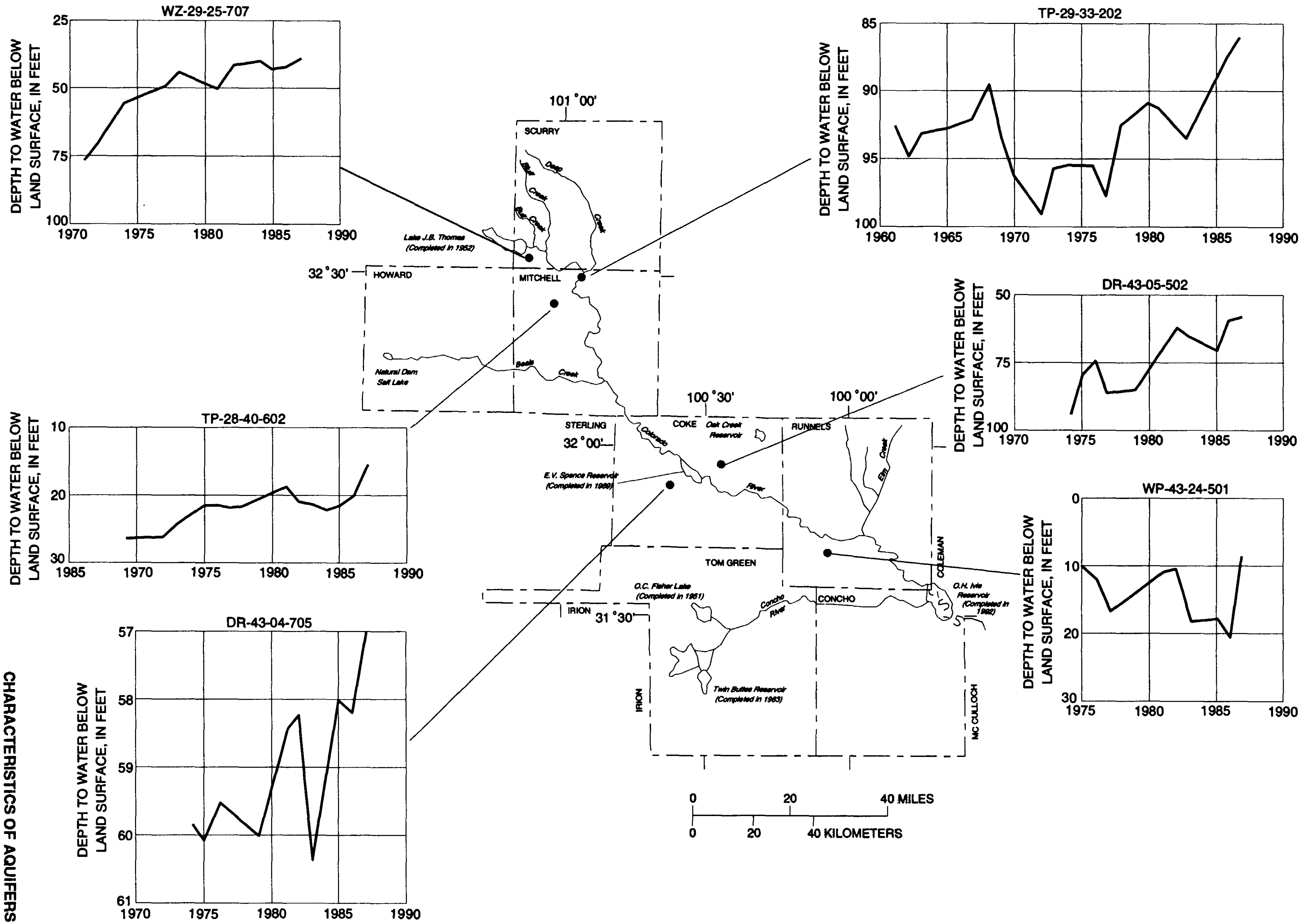


Figure 13. Hydrographs of water levels in selected observation wells.

1,000 mg/L recommended secondary constituent level for dissolved solids in drinking water established by the Texas Department of Health (1988). About 336 of the wells and springs (about 87 percent) had water with specific-conductance values exceeding 704 µS/cm, which is comparable to an estimated dissolved-solids concentration of about 500 mg/L. This value equals the SMCL for dissolved solids in public supplies established by the National Secondary Drinking-Water Regulations (U.S. Environmental Protection Agency, 1990a). Specific conductance values measured during 1986 may have been decreased because of dilution by recharge from greater than normal precipitation. In comparison, about 76 percent of the 1,120 historical analyses from the TWODB and other sources had dissolved-solids concentrations that exceeded 1,000 mg/L.

The specific-conductance values and estimated dissolved-solids concentrations for water from wells and springs measured in 1986 were consolidated with results from historical analyses by the TWODB to assess areal variations in estimated dissolved-solids concentrations of shallow-aquifer water in the study area. Evaluation of these data indicated that water from most wells and springs with large estimated dissolved-solids concentrations were near sites with much smaller values. Wells and springs with water having large estimated concentrations were not always clustered in common areas or located in common formations.

Temporal trends in estimated dissolved-solids concentrations in water from the shallow aquifers were difficult to identify because (1) periodic changes in hydrologic and seasonal conditions caused fluctuations in shallow-aquifer water quality, and (2) only a few water-quality analyses have been made over any length of time for any one of the wells in the study area. The high water levels in 1986 and 1987 (fig. 13) probably were caused by greater than normal precipitation and resultant recharge. The recharge water increased the volume of shallow-aquifer water and thus reduced dissolved-solids concentration. Therefore, calculations of historical changes in salinity were not considered valid for water samples from the shallow aquifers.

Principal Sources of Dissolved Solids

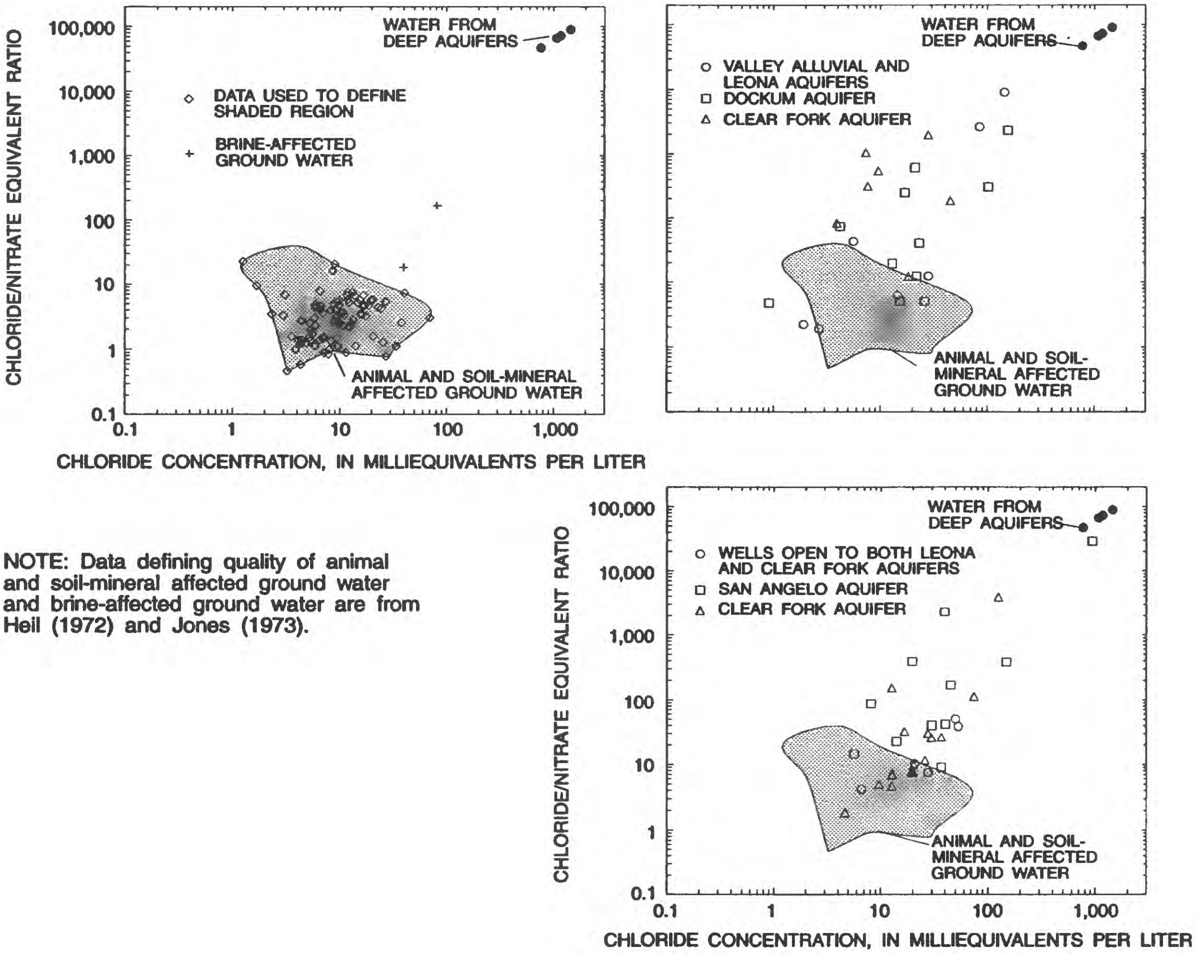
Dissolution of halite or mixing with deep-aquifer water was the most common source of elevated concentration of dissolved solids in 48.0 percent of 77 samples from shallow aquifers classified using salt-norm analysis (fig. 11). The second most common source of dissolved solids in shallow-aquifer water (41.6 percent of the samples) was from the weathering and dissolution of sulfate minerals. Other sources classified using salt-norm analysis accounted for 10.4 percent of the dissolved solids.

Using the Cl/NO_3 ratio method of classifying water affected by mixing with deep-aquifer brine, the ratio for brine-affected ground water (fig. 14) is much larger than that for water affected by dissolution of unsaturated-zone salts (Heil, 1972; Richter and Kreitler, 1985; Richter and others, 1990). The brine-affected water had a proportionately larger concentration of chloride relative to nitrate and much larger concentrations of chloride than the samples affected by other processes.

Water from soil-mineral dissolution was classified using trace-species/chloride ratios as the principal source of chloride (28.4 percent) among 67 shallow-aquifer samples with nitrate determinations (fig. 15). The principal sources of chloride in other samples included water from: (1) Pennsylvanian System and Permian System deep aquifers, 17.9 percent; (2) Permian System deep aquifers, 11.9 percent; and (3) Pennsylvanian System deep aquifers, 10.4 percent. Water samples with nitrate determinations and for which the principal source of chloride could not be classified constituted 17.9 percent of the 67 samples.

Water from Pennsylvanian System deep aquifers was classified using trace-species/chloride ratios as the principal source of chloride in 24.4 percent of 45 shallow-aquifer samples lacking nitrate determinations (fig. 15). The principal sources of chloride in other samples were less than 10 percent each of the total. Water samples that lacked nitrate determinations and for which the principal source of chloride could not be classified constituted the greatest percentage (44.4 percent) of the 45 samples. Water from a deep aquifer was classified using trace-species/chloride ratios as the principal source of chloride in more than 40 percent of all the shallow-aquifer samples.

Water samples from wells 28-44-101 and 28-52-103 in the Valley alluvial aquifer were classified by salt-norm analysis as having dissolved solids resulting from the weathering of sulfate minerals (table 3). Water samples from wells 28-52-504 and 28-52-702 were classified by salt-norm analysis as having deep-aquifer brine as the source of dissolved solids (table 3). Water from these latter two wells also obtained chloride from



NOTE: Data defining quality of animal and soil-mineral affected ground water and brine-affected ground water are from Heil (1972) and Jones (1973).

Figure 14. Relation of chloride/nitrate equivalent ratios to chloride concentrations in potential chloride sources and in water from shallow aquifers in the upper Colorado River Basin, Texas.

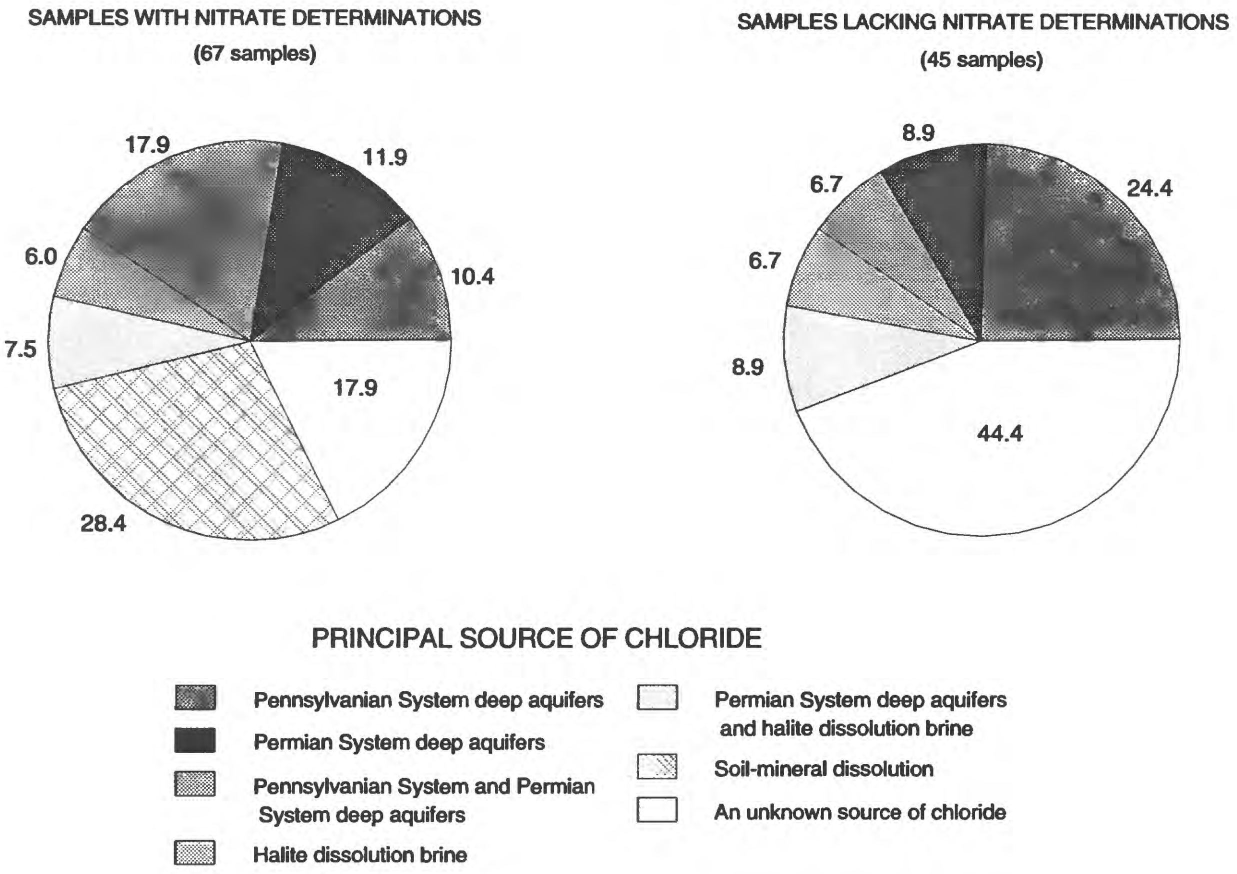


Figure 15. Principal sources of chloride, in percent, for shallow-aquifer samples from the upper Colorado River Basin, Texas, classified using trace-species/chloride ratios.

water from Pennsylvanian System deep aquifers (table 4).

A water sample collected in 1989 from well 28-44-101 was classified using Br/Cl ratios as obtaining its chloride from a halite dissolution brine (table 4). The 1989 sample from this well was used to classify the source of chloride because it had a larger chloride concentration than the 1987 sample. The depth to water at this well was less than 5 ft before sample collection (table 1). Mount and others (1967) have indicated that evapotranspiration from a shallow water table in this aquifer caused precipitation of gypsum and other evaporite salts in the unsaturated zone. Dissolution of these salts into infiltrating water or as a result of a rise in water table, therefore, probably was caused by the dissolved solids in water from well 28-44-101. Similar evidence also indicated the unsaturated-zone minerals as the principal source of dissolved solids and chloride in a 1989 sample of water from well 29-59-701 in the Valley alluvial aquifer overlying the Guadalupe Series.

Salt-norm analysis results classified water from wells in the Valley alluvial aquifer overlying the Dockum Group as similar to water affected by dissolution of sulfur-bearing minerals (table 3). The three water samples had saturation indices with respect to gypsum that ranged from -0.14 to 0.02, an indication of near-saturated to saturated conditions. The samples also were oversaturated with respect to calcite, having saturation indices ranging from 0.3 to 0.7. The data indicate that gypsum dissolution or pyrite oxidation and dissolution were important processes affecting the salinity of shallow-aquifer water in these wells. The depth to water in these wells ranges from 82.2 to 94.5 ft below land surface (table 1). Evaporative concentration of shallow-aquifer water, therefore, was not a process affecting the salinity in these water analyses.

Salt norms for water from well 28 in the Leona aquifer (table 3) indicated an origin of dissolved solids from dissolution of sulfur-bearing minerals. Salt norms of water samples from four of five wells open to both the Leona and Clear Fork aquifers were similar to those for water affected by mixing with deep-aquifer brines. Water from well 28 in the Leona aquifer and from wells 25, 27, and 38, open to both the Leona and Clear Fork aquifers, derived their chloride from unsaturated-zone minerals (table 4). The Cl/NO_3 equivalent ratios from these four water samples were all in the range typical of soil-zone-derived chloride and nitrate. The remaining two water samples, from wells 42 and 53b, derived their chloride from water from Pennsylvanian System deep aquifers according to the Br/Cl ratio.

Salt-norm classifications of 9 of 17 samples from the Dockum aquifer were brine or brine-mixed (table 3). The principal source of dissolved solids in these nine water samples was water from deep aquifers. The source of chloride for water samples from wells 28-55-101 and 29-25-707 in the Dockum aquifer (table 4) was classified exclusively as water from Pennsylvanian System deep aquifers.

Sulfur-bearing minerals were classified as the principal source of dissolved solids in 8 of 17 salt norms of water samples from the Dockum aquifer (table 3). The salt norm of water from well 29-41-705, which was typical of many water samples from the Dockum aquifer, was dominated by normative alkali and magnesium sulfate salts, with smaller proportions of normative halite and normative anhydrite (fig. 16). Pyrite has been indicated as a source of much of the sulfate in Dockum ground water (Dutton and Simpkins, 1986). Sulfur-bearing minerals also were classified as the principal source of dissolved solids in salt norms of water from six of seven wells in the Whitehorse-San Andres aquifer (table 3). A typical salt norm (well 43-03-904) was dominated by normative anhydrite, with smaller proportions of normative alkali and magnesium sulfate salts and normative halite (fig. 16). Gypsum is abundant in the several formations comprising the aquifer (Jones, 1953). Water samples from this aquifer also generally were nearly saturated with respect to gypsum and oversaturated with respect to dolomite and calcite (fig. 12). These data indicated that the large proportion of sulfate in the water originated from gypsum dissolution.

A water sample from well 29-59-505 in the Whitehorse-San Andres aquifer was classified as similar to deep-aquifer brine by salt-norm analysis (table 3). However, the source of chloride in a 1989 water sample from this well, classified using Br/Cl ratios, could not be distinguished between water from Permian System or Pennsylvanian System deep aquifers (table 4). Water samples from wells 29-50-603 and 29-58-611, which contained sufficient chloride to allow interpretation using Br/Cl ratios, indicated that chloride was derived from water from Permian System deep aquifers exclusively or in combination with halite dissolution brine.

Deep-aquifer brine was classified by salt-norm analysis as the principal source of dissolved solids in water from seven wells and one spring from the San

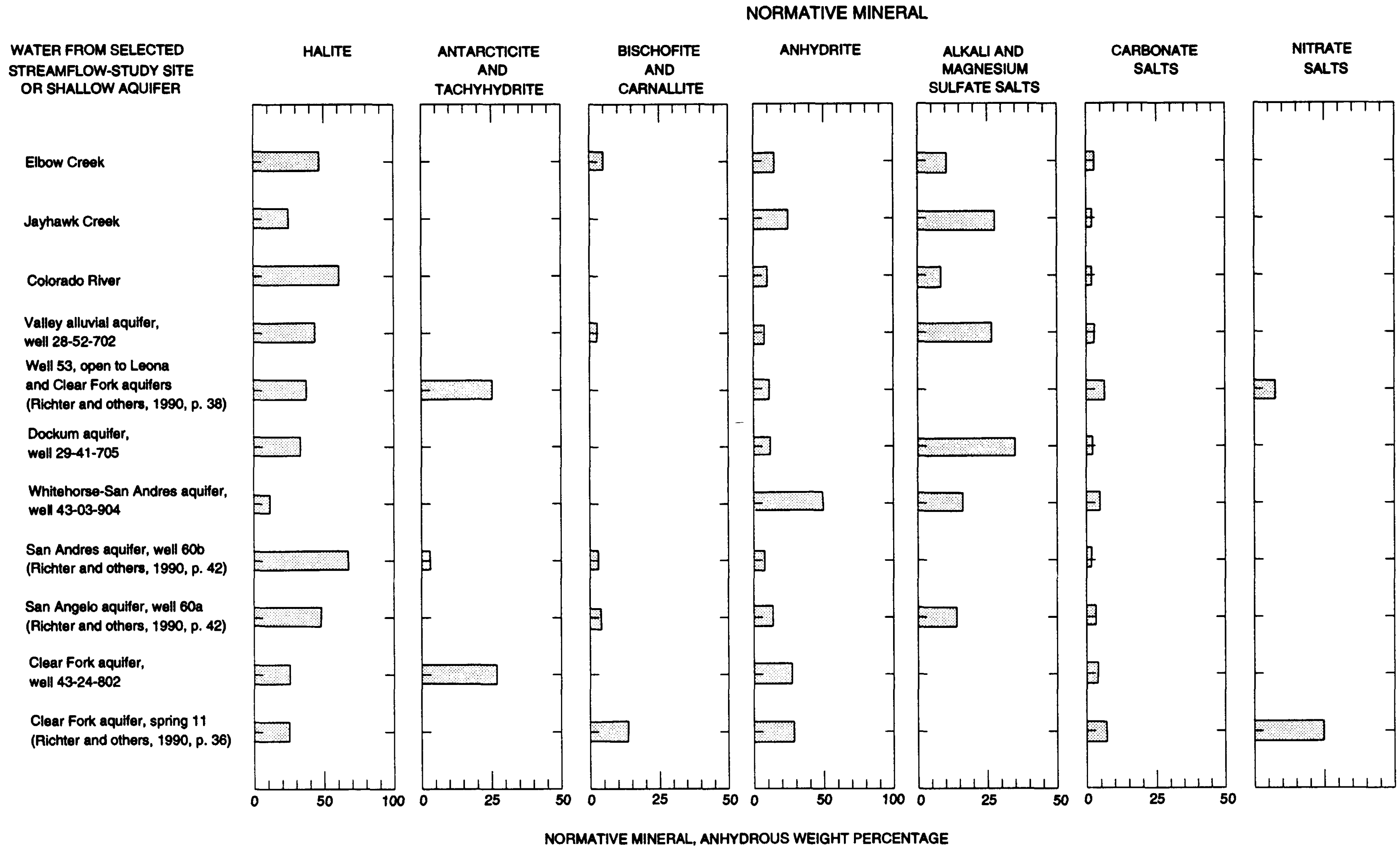


Figure 16. Anhydrous weight percentages of normative minerals for water from selected streamflow-study sites and shallow aquifers in the upper Colorado River Basin, Texas.

Angelo aquifer (table 3). The salt norm of a shallow brine from the San Angelo aquifer at well 60b was dominated by normative halite (fig. 16). Sulfur-bearing minerals were determined to be the principal source of dissolved solids in salt norms of water from wells 43-05-502 and 43-13-304 in the San Angelo aquifer.

Water from Permian System deep aquifers was classified as the principal source of chloride in five of the eight samples from the San Angelo aquifer with brine or brine-mixed salt norms (tables 3 and 4). Water from spring 43-14-102 obtained chloride from water from Pennsylvanian System deep aquifers. The source of chloride could not be distinguished between water from Pennsylvanian System and Permian System deep aquifers in analyses from wells 35, 37, and 43-13-304.

Sulfur-bearing minerals were classified by salt-norm analysis as the principal source of dissolved solids in 7 of 21 water samples from the Clear Fork aquifer and in 1 of 4 samples probably from the Clear Fork aquifer. The origin of the sulfate may be related to the dissolution of gypsum from deposits such as those in the Arroyo Formation in the Clear Fork aquifer (Sellards and others, 1933).

Unsaturated-zone minerals were classified using trace-species/chloride ratios as the principal source of chloride in nine water samples from or probably from the Clear Fork aquifer (table 4). These water samples all had Cl/NO_3 equivalent ratios less than 10. A total of 17 samples from or probably from the Clear Fork aquifer indicated that the salinity is from mineral dissolution. In water samples obtained from saline springs 10, 11, 12, and 14 (table 3) the salt norm contained similar proportions of the normative minerals bischofite and carnallite as is shown for spring site 11 (fig. 16). These normative minerals commonly are present in salt norms of water affected by evaporation (Bodine and Jones, 1986). The depths to water near the four springs were sufficiently shallow to indicate evaporative accumulation and dissolution of unsaturated-zone salts resulting from a rise in water table as the likely source of their dissolved solids (Richter and others, 1990).

Water samples from wells 40, 42-02-701, and 43-24-802 were classified using Br/Cl ratios as obtaining their chloride from water from Pennsylvanian System deep aquifers (table 4). The source of the chloride was classified using Br/Cl ratios as water from Permian System deep aquifers in analyses from wells 4 and 36. A chloride source could not be distinguished between water from Permian System and Pennsylvanian System deep aquifers in analyses from wells 39 and 41.

Samples of water from five wells in the Clear Fork aquifer that derived their salinity from dissolution of sulfur-bearing minerals contained sufficient chloride to enable classification using the trace-species/chloride ratios. An analysis of water from well 43-40-601 indicated that the water obtains chloride by mixing with water from Pennsylvanian System deep aquifers. The source of the chloride could not be distinguished (1) between waters from Permian System and Pennsylvanian System deep aquifers in samples from spring site 15 and well 13, and (2) between water from Permian System deep aquifers and halite dissolution brine in samples from wells 43 and 43-24-501.

Classifications of sources of chloride in shallow aquifers by trace-species/chloride ratios were areally and temporally variable. Of the 29 wells and 1 spring that were sampled twice during the study, water from only 12 wells and the spring maintained the same classification of the source of chloride between the 1987 and 1989 data. Classifications of the source of chloride differed between 1987 and 1989 samples at eight wells because of differences in chloride concentrations. The samples with the largest chloride concentration in each pair was used for the classification because of its greater similarity to mixtures of two or fewer chloride sources. The inclusion of nitrate determinations for the 1989 samples also changed the classifications of the sources of chloride between 1987 and 1989 analyses.

Deep Aquifers

Ten deep aquifers (pl. 6) were identified on the basis of their salinity and oil and gas production discussed previously. Locations of major oil and gas fields with production from one or more of the deep aquifers also are shown on plate 6. Each of the deep aquifers contains at least one hydrocarbon-bearing formation. The Whitehorse-San Andres and the San Angelo deep aquifers are grouped together in parts of the area shown on plate 6 because of differences in the way oil and gas production data and water-quality data were compiled.

Potentiometric Surfaces

Potentiometric surfaces based on formation-test data before 1965 were developed by McNeal (1965) for five of the deep aquifers--the San Andres Formation of the San Angelo aquifer, and the Wolfcamp, Strawn, Mississippian, and Ellenburger aquifers. The potentiometric surfaces presented by McNeal (1965) dip to the east. McNeal concludes that the surfaces do not differ by more than 200 ft from unit to unit, indicating small potential for vertical movement of water between deep aquifers. However, throughout most of the study area, the potentiometric surface for each deep aquifer exceeded the water-level altitude of the overlying shallow aquifer.

The altitude of the potentiometric surfaces for 1965 ranged from about 2,700 to 3,000 ft at the western boundary of the study area to about 1,600 ft at the eastern boundary. The potentiometric surfaces of the deep aquifers exceeded the water-level altitude of the shallow aquifers (pl. 3) throughout Howard, Mitchell, and Scurry Counties. In the eastern one-half of the study area, however, the altitude of the deep-aquifer potentiometric surfaces exceeded the water-level altitude only in topographically low areas. Because the water-level altitude parallels the topography, it slopes toward the Colorado River and major tributaries, whereas the potentiometric surfaces slope gently to the east. Throughout the valleys along the Colorado River and major tributaries, the altitude of the potentiometric surfaces of the deep aquifers exceeded the water-level altitude of the shallow aquifers by about 100 ft near Stacy to as much as 500 ft in Scurry County.

As of 1986, about 3 billion bbl of oil had been produced in the major counties of the study area--Coke, Concho, Howard, Mitchell, Runnels, Scurry, and Tom Green (Dallas Morning News, 1987). As of 1965, however, only about 42 percent (about 1.3 billion bbl) of that oil had been produced. Oil and gas production probably have contributed to pressure declines that have lowered potentiometric surfaces since 1965. Oil- and gas-well test data collected between 1965 and 1990 indicate that potentiometric surfaces of deep aquifers generally were lower in 1990 than in 1965.

Chemical Characteristics

Chloride and sodium were the dominant anion and cation in water samples from the deep aquifers in the brine analyses file. Chloride typically composed more than 90 percent of the anionic equivalent charge and sodium typically composed between 70 and 90 percent of the cationic equivalent charge. Major constituents that composed most of the remaining equivalent charge in solution included calcium, magnesium, and, in some samples, sulfate. Other minor constituents that were present in most deep-aquifer water samples in concentrations greater than 1 mg/L included bromide, iodide, boron, lithium, manganese, strontium, and organic carbon, which is given as total organic carbon and as the aliphatic acid anions, acetate and propionate. Water-quality data for samples from three of the deep-aquifer wells are listed in table 1. Water samples from the San Angelo, Clear Fork, Wolfcamp, Canyon, and Strawn deep aquifers typically were near saturation (saturation index of zero) to oversaturated (saturation index greater than zero) with respect to calcite and dolomite and undersaturated (saturation index less than zero) with respect to halite (fig. 17). One or more samples from each of these deep aquifers were at or near saturation with respect to gypsum.

Salt norms of typical water samples from each of the deep aquifers were similar to those from water samples associated with deep sedimentary basins and very saline strata (Bodine and Jones, 1986, p. 45). These salt norms were dominated by normative halite and contained more than 5 percent of the sum of normative antarcticite and normative tachyhydrite. The cation chemistry of water with these salt norms may have been influenced by the diagenetic alteration of silicate and carbonate minerals. The salt norms of these water samples also differed substantially from salt norms influenced by gypsum dissolution, mixing of brine and freshwater, and halite dissolution brine (fig. 18). The deep-aquifer water samples shown in figure 18 are samples with dissolved-solids concentrations within 5 percent of the median concentration for that deep aquifer.

The saturation state and salt norms of deep-aquifer water indicated that chloride was the only major ion useful for tracing deep-aquifer brine influences on surface and shallow-aquifer water. All other major-ion concentrations were affected greatly by reactions with aquifer minerals.

The following dissolved-solids concentrations from the brine analyses file were used to describe the salinity characteristics for water in each of the deep aquifers.

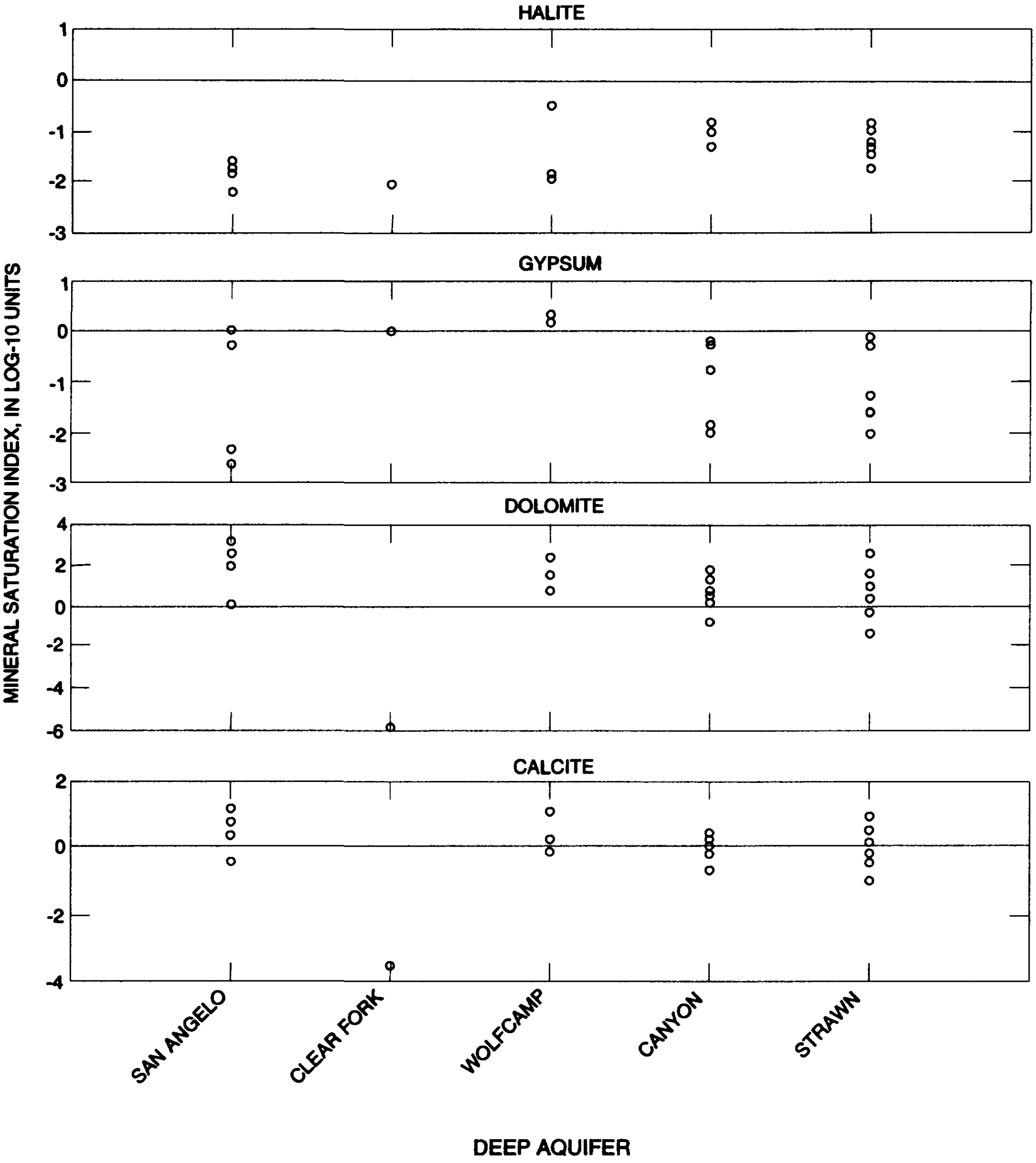


Figure 17. Dotplots showing mineral-saturation indices for water from deep aquifers in the upper Colorado River Basin, Texas.

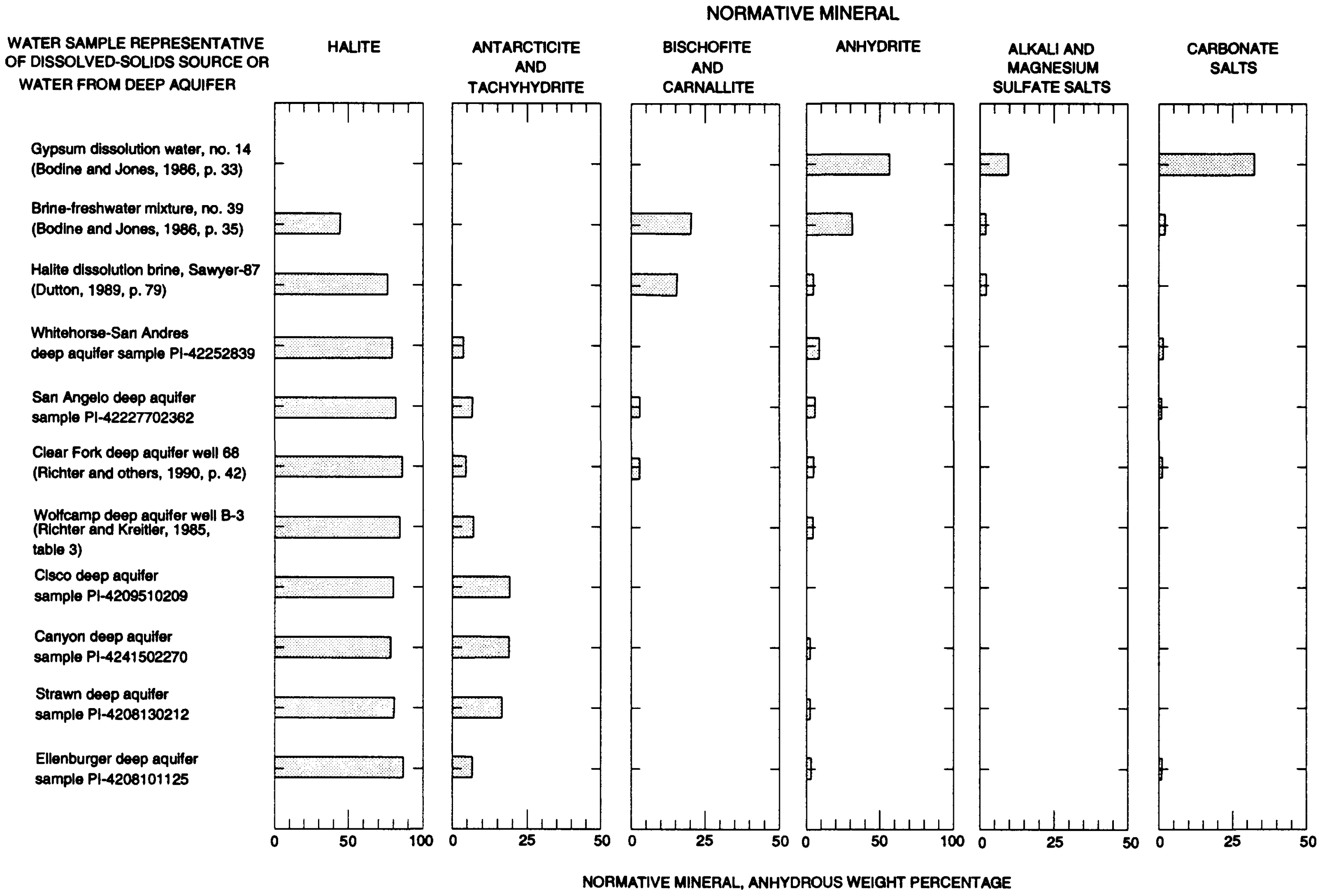


Figure 18. Anhydrous weight percentages of normative minerals for water samples representative of selected sources of dissolved solids and deep aquifers in the upper Colorado River Basin, Texas. (PI samples data supplied by Petroleum Information Corp., written commun., 1990.)

Deep aquifer	Number of analyses	Dissolved-solids concentrations (milligrams per liter)		
		Mean	Maximum	Minimum
Whitehorse-San Andres	12	61,200	174,000	17,200
San Angelo	109	78,700	203,000	12,200
Clear Fork	14	73,900	163,000	15,700
Wolfcamp	7	117,000	283,000	53,200
Cisco	14	83,100	158,000	59,700
Canyon	135	89,600	220,000	9,100
Strawn	227	128,000	229,000	3,650
Ellenburger	16	72,000	111,000	50,700

The mean dissolved-solids concentration of water from the deep aquifers ranged from 61,200 to 128,000 mg/L. The mean of the 534 dissolved-solids concentrations was 102,000 mg/L.

PROCESSES AFFECTING THE SALINITY OF WATER

Processes affecting the salinity in Colorado River water from the study area include evapotranspiration, dissolution of minerals from unsaturated and saturated zones of shallow aquifers, mixing with brines from deep aquifers, and movement of water through saline soils and as saline seeps. Large differences in dissolved-solids concentrations in water from wells in close proximity to the river system indicate that the processes contributing to salinity were site specific. There was no evidence of deposition of dissolved solids from precipitation or winds, thus contributions from the atmosphere were considered small. Salt-norm analyses, however, indicate that ground water classified as brine was in close proximity to sites of oil and gas production.

Evapotranspiration

Evapotranspiration is the process by which water is removed from water surfaces, moist soil, and plants, and returned to the atmosphere as water vapor leaving behind the dissolved solids. The mean-annual potential evapotranspiration in the study area ranges from about 36 to about 39 in. (Geraghty and others, 1973). The mean-annual gross lake-surface evaporation for 1940-65 ranged from about 78 in. for the northern part of the study area to about 82 in. for the southern part. Net lake evaporation during this period varied from about 58 in. for the eastern part to about 65 in. for the west (Kane, 1967). High temperatures and high-velocity winds produce substantial rates of evapotranspiration that combine with periods of little precipitation to further reduce water availability during droughts.

An elementary water-budget analysis was performed for the study area to estimate the volume of evapotranspiration on the basis of precipitation and runoff. Possible sources of inflow to the study area were precipitation, movement of water through the shallow aquifers, and movement from the deep aquifers to the shallow aquifers. Movement of shallow-aquifer water to or from the study area through the shallow subsurface probably was minimal based on the gradient of the water-level altitude (pl. 3). Brine from deep aquifers may have been only a small part of recharge to shallow aquifers as indicated by dissolved-solids concentrations of water from inventoried wells in the shallow aquifer. Thus, inflow to the study area primarily was precipitation, and outflow from the study area primarily was streamflow, evapotranspiration, and a small amount as recharge to deep aquifers.

The mean-annual precipitation for 1969-86 at the 11 gages was 23.3 in. (fig. 5). Runoff from the study area was represented by the mean streamflow of 211 ft^3/s for 1969-86 at station 08136700 (fig. 5), which represented a mean-annual depth of 0.49 in. over the study area, or about 2 percent of precipitation. The remaining 98 percent of precipitation was attributed largely to evapotranspiration.

The evaporation component of evapotranspiration may result in an increase in the salinity of shallow-aquifer water, ponded runoff, and irrigation return flow. Evaporation of water from the land surface increases dissolved-solids concentrations in remaining water, and also increases deposition and accumulation of precipitates on the land surface and particle surfaces in the unsaturated zone. Evaporation can increase salinity only where water is available for evaporation, such as topographically low areas of shallow-aquifer water, topographically low areas where runoff can be ponded, and areas of large application of irrigation water.

Shallow-aquifer water can provide a constant source of water for evaporation. Water at depths of as much as 10 ft in some soils may evaporate through the capillary fringe, which is the zone of wetted soils immediately above the water table where water is held by surface tension (Ripple and others, 1973). Many springs and areas of shallow-aquifer water, primarily in topographically low areas, were identified in Howard, Mitchell, and southern and eastern Runnels Counties from a 1986 inventory (pl. 4).

Ponded runoff from storms can be a source of water for evaporation although only a few storms per year produce ponds in the study area. It is not unusual for many ponds, especially on small tributaries, to exist without inflow or outflow for many weeks after a storm. Much of the dissolved solids in ponded water may infiltrate to shallow ground water locally as a result of infiltration of the ponded waters, or from infiltration of water from subsequent smaller rains that do not flush the solids to receiving streams.

Irrigation provides a third source of water for evaporation. Evaporation of irrigation water is not considered a major regional source for shallow saline water or the cause of temporal increases in dissolved-solids concentrations in surface or shallow-aquifer water because only about 1 percent of the area is irrigated. Also, surveys of irrigation water use by counties since 1958 indicate no large changes in the amount of land area irrigated (Texas Water Development Board, 1986).

Transpiration is the process by which water vapor escapes from living plants and enters the atmosphere. Water transpired from plants comes from soil moisture supplied from precipitation, irrigation, and from streamflow and shallow-aquifer water. Most transpiration in the area is associated with brush (woody plants) and to a lesser extent, with rangeland grasses and crops. About 60 percent of the area is covered with rangeland grasses, but the type and densities of the grasses are not well documented, thus, estimates were not made for transpiration by grasses.

Phreatophytes use soil moisture primarily from surface and shallow ground waters. Much of the transpiration by brush is along major streams where phreatophytes, primarily salt cedar and mesquite, are abundant throughout most reaches. In the study area before 1969, about 24,600 acres or 72 percent of the 34,200 acres in the flood plain of the Colorado River were covered with various densities of mesquite (Larner and others, 1974). As of 1969, about 16,300 acres of mesquite had been cleared or sprayed, leaving 8,300 acres mostly in areas where the density of mesquite was high. Much mesquite has replaced that which was cleared or treated, and no known efforts have been made to control its growth since 1969. Mesquite covers most reaches of every stream in the study area, particularly in the eastern part of the study area, where salt cedar is less dense (Robert Fowler, U.S. Soil Conservation Service, oral commun., 1989). Although located throughout the study area, mesquite is considered a phreatophyte only in the flood plain.

In Texas, salt cedar grows only along streams and thrives in saline-water environments. Along the Colorado River, decreasing densities of salt cedar downstream are associated with decreases in salinity of the water. The spread of salt cedar is considered to be caused partly by the addition of reservoirs along the Colorado River. The resultant decrease in the magnitude and frequency of floods, because of the reservoirs, is favorable to the growth of salt cedar and other phreatophytes along the shorelines of the lakes and reservoirs (Larner and others, 1974).

Prior to 1950, salt cedar was confined to a few areas in small thickets; however, from 1950 to 1969, areal coverage increased at least 500 percent (Larner and others, 1974). As of 1969, salt cedar of various densities covered 1,450 acres in the Colorado River flood plain. As of 1982, salt cedar covered about 10,000 acres in the Colorado River flood plain and about 2,500 acres in the Beals Creek flood plain in the study area (Dan Caudle, U.S. Soil Conservation Service, written commun., 1989). Salt cedar in the most upstream one-third of the reach of the Colorado River in the study area is dense, the middle one-third is moderate, and the downstream one-third is sparse. Beals Creek has a sparse density of salt cedar throughout the area (U.S. Soil Conservation Service, 1985).

The lengths of the reaches of the Colorado River, Beals Creek, Elm Creek, and the Concho River in the study area are 239, 13, 10, and 33 mi, respectively. The flood plain along the Colorado River covers 34,200 acres, and an additional 11,000 acres is included for the flood plain around E.V. Spence Reservoir. Flood plains for Beals Creek, Elm Creek, and the Concho River cover about 3,200, 1,200, and 12,000 acres, respectively. A total of 61,600 acres of flood plain along the four streams is covered by salt cedar and mesquite: The transpiration rate from phreatophytes across the flood plain of the four major streams is estimated to be 29.6 in/yr, on the basis of the coverage data for salt cedar and mesquite and the Blaney-Criddle formula (Rantz, 1968). This transpiration rate represents 152,000 acre-ft/yr or 210 ft^3/s and is comparable to the mean flow of the Colorado River discharging the study area at station 08136700 (fig. 5).

Salt deposits can accumulate in the shallow subsurface or on the land surface as a result of transpiration. Salt accumulates near roots in the subsurface because many plants absorb only small amounts of the dissolved solids. The salt deposits can wash to receiving streams or be flushed back to shallow-aquifer water. Salt cedar, however, absorbs salts and excretes them on stem and leaf surfaces (Hem, 1967). Those salts then can be washed from the plant by rain or blown off by wind. Thus, some salt deposits on land surfaces may be caused by transpiration from salt cedar (fig. 19).

Evapotranspiration can be a major site-specific contributor to salinity in shallow aquifers in reaches along major streams, in areas of shallow aquifers with depths to water of less than about 10 ft, and in irrigated areas. These sites represent only a small part of the study area; thus, evapotranspiration is not considered a major regional contributor to shallow-aquifer salinity. Also, the large differences in dissolved-solids concentrations of water in proximate wells are less likely to be associated with a regional process such as evapotranspiration.

Dissolution of Minerals

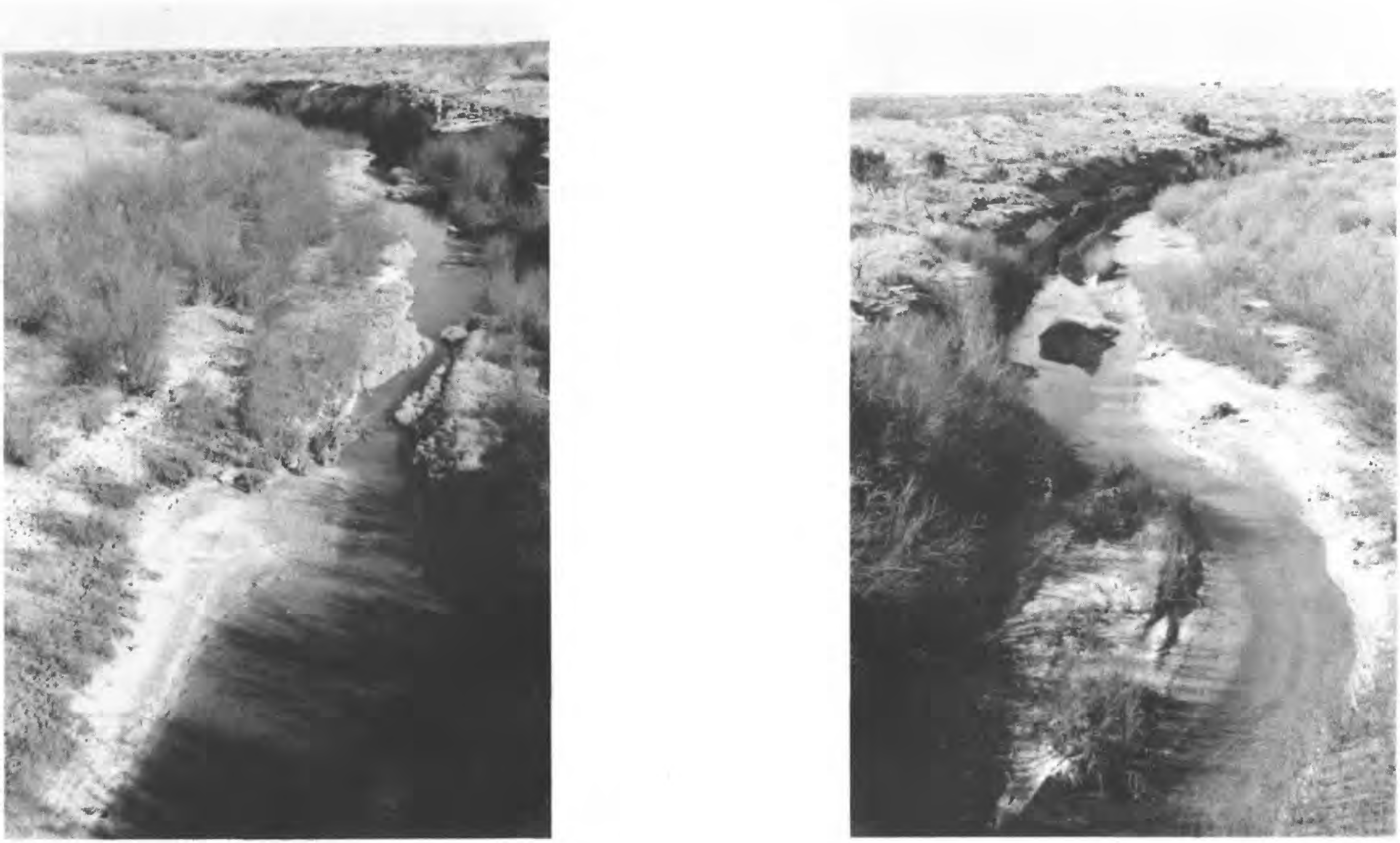
Dissolution of water-soluble major and trace minerals in aquifers can contribute substantially to salinity in streamflow and shallow-aquifer water. For example, several shallow aquifers in the study area include stringers, lenses, and beds that contain the sulfur-bearing minerals gypsum and pyrite as minor lithologic components. These shallow aquifers are the: Valley alluvial aquifer (Mount and others, 1967); Dockum aquifer (Dutton and Simpkins, 1986); Whitehorse-San Andres aquifer; and Clear Fork aquifer (Sellards and others, 1933). These and other soluble minerals may be dissolved from the unsaturated zone by recharge or by an increase in water levels. Freshwater also may increase dissolution of these minerals in the saturated zones, causing the dissolved-solids concentration to increase until the water becomes saturated with respect to the mineral or exhausts the supply of the dissolving mineral.

Dissolution of disseminated evaporite minerals from the unsaturated zone also is a possible source of dissolved solids in shallow aquifers. Jones (1973, p. 129-177) has documented 37 locations in Runnels County where concentrations of "water-leachable chloride" were greater than 18 mg/kg in core samples from the unsaturated zone. The water-leachable chloride possibly represents evaporite minerals that accumulated over many years by evaporation of infiltrating water. Soluble minerals that could accumulate on existing mineral or grain surfaces in such an environment include halite, gypsum, and complex evaporative salts composed of a suite of elements.

Jones (1973, p. 124-214) also documented the presence of nitrate salts in the unsaturated zone. Concentrations of nitrate salts ranged from about 10 mg/kg in pasture soils to more than 700 mg/kg in soils below barnyards. These and other soluble minerals, such as halite, are not expected in large concentrations below the water table of the shallow aquifers except in low-permeability deposits isolated from rapid ground-water flow. Jones (1973) indicated that nitrate salts dissolved by the recently elevated water table (1950 to present) might be related to ground-water salinity in Runnels County. In the classification of water affected by the soluble salts found in soil cores taken from the unsaturated zone of southern Runnels County, the Cl/NO_3 equivalent ratios typically ranged from less than 1 for cultivated land and pasture to about 3 for soils near concentrated applications of animal waste such as septic tank laterals and cattle feedlots (Jones, 1973, p. 129-177). Large Cl/NO_3 equivalent ratios may be caused by nitrate-depleting processes such as denitrification. Denitrifying conditions could be present where shallow-aquifer water mixed with deep-aquifer water or oil-production brines that were oxygen-depleted and organic-carbon-enriched. Interpretations by Jones (1973) and Kreitler and Jones (1975) indicated that denitrification was not an important transformation process for nitrates in shallow ground water of southern Runnels County in the study area. Data that define the range of Cl/NO_3 equivalent ratios in ground water from Heil (1972) and Jones (1973) are shown in figure 14.

Mixing With Brines

Brine, defined as water that has a dissolved-solids concentrations greater than 35,000 mg/L (Winslow and Kister, 1956), is present in every deep aquifer in the study area. The three major mechanisms of brine movement to the surface or shallow subsurface are natural discharge, leakage through wells and boreholes, and the disposal of brine produced with oil and gas. Brine can discharge naturally to the surface or into



A. View of the Colorado River downstream from bridge on State Highway 350. White material on left bank is salt deposits. Brush is salt cedar. Streamflow-gaging station visible in upper right corner.

B. View of Colorado River upstream from bridge on State Highway 350. White material on banks is salt deposits.

Figure 19. Salt deposits on the banks of the Colorado River near Ira, Texas.

shallow aquifers where the potentiometric head of the brine in deep aquifers sufficiently exceeds the water-level altitude of the shallow aquifer and where confining layers are absent. Deep wells and boreholes, related to exploration and production of oil and gas, that are not properly cased, sealed, or plugged can provide conduits for upward movement of natural and injected brine. A report by Reed (1961, p. 20) concluded, "a great percentage of the total mineral content of the brines produced with the oil in the watershed of the Colorado River does eventually find its way into the Colorado River itself."

The Coleman Junction Limestone, a member of the Putnam Formation and part of the Wolfcamp deep aquifer, provides a major potential source of shallow brine in eastern parts of the study area. The Coleman Junction Limestone, which crops out in Coleman County just east of Runnels County, averages 275 ft in thickness and ranges from 800 to 2,600 ft in depth below land surface beneath the study area (Shamburger, 1959). Oil and gas wells in all major oil fields in Concho, Runnels, and Tom Green Counties produce oil from the Pennsylvanian System and penetrate the shallower Coleman Junction Limestone. Pressures in the oil and gas wells are large enough to move brine to the surface throughout the counties (Shamburger, 1959, p. 13-15).

Richter and others (1990) also reported that much potential for movement of brine to land surface exists throughout Runnels and southeastern Tom Green Counties. Seven analyses indicated the dissolved-solids concentrations for the Wolfcamp deep aquifer ranged from about 53,200 to 283,000 mg/L. The Coleman Junction Limestone is a potential source of brine to the surface and shallow subsurface in the eastern part of the study area because of its large dissolved-solids concentration and pressure gradient.

The drilling, completion, and abandonment of all oil- and gas-related boreholes are regulated by rules of the Railroad Commission of Texas (1989). About 90 percent of the complaints filed with the Railroad Commission involved brine contamination and 10 percent involved contamination from oil or drilling fluids (Texas Department of Agriculture, 1985). Summaries of all 1,789 complaints pending as of November 1984, and summaries of 2,869 (about one-half) of all complaints resolved between January 1982 and November 1984 were reviewed. About 73 percent or 3,375 complaints were in six categories, which indicate the relative frequency of the most common sources of brine contamination:

Category	Number of complaints	Percent of complaints[1]
Abandoned wells	969	21
Leaks	699	15
Pits	639	14
Spills	514	11
Disposal	331	7
Abandoned wells with abandoned pits	223	5
Remaining	1,283	28

[1] Totals more than 100 percent because of rounding.

Natural Discharge

On the basis of oil- and gas-well test data collected between 1965 and 1990, the potentiometric surfaces of deep, brine-containing aquifers exceed the land surface in about 20 to 40 percent of the aquifers, thus there is a potential for leakage of brines to the surface or shallow aquifers. However, no data were obtained showing natural discharge of brines to the surface in the study area, which may result from the depth of brine aquifers and their resistance to upward movement because of the many confining layers in the Triassic, Permian, and Pennsylvanian Systems.

Data collected prior to most oil-field development indicate the presence of shallow brine under natural conditions. For example, two water-quality analyses from shallow wells in Tom Green County indicate oil-bearing brine within about 230 ft of the surface in the San Angelo Sandstone (Udden and Phillips, 1911). Also, brine was reported to flow into a 1,000-ft deep well at 300 ft below land surface (Richter and others, 1987).

Most evidence indicates that the salinity in shallow aquifers is not caused by mixing with brines moved to the shallow subsurface as natural discharge from deep aquifers. Reed (1961) made an intensive study of the sources of salinity in the Colorado River in Scurry and Mitchell Counties, which have the most saline surface and shallow-aquifer water in the study area. Reed's study was based on interpretations of water-level and water-quality data from 92 wells and 69 test boreholes and interpretations of water-quality analyses at 35 sites on the Colorado River and tributaries. Reed also used aerial photographs, core tests, and geologic outcrops in his study of the natural salinity of the Colorado River. His examination of the upper 250 ft of Triassic sediments in the two-county area indicated that these sediments were deposited in a freshwater environment and that the chloride concentration of water in the system generally was less than 300 mg/L (Reed, 1961). He also ruled out the possibility of leakage from the deeper Permian System through faults or fractures. Reed (1961, p. 20) concluded, "there is no known source of salt water to the river with chlorides significantly higher than 500 parts per million."

Leakage Through Wells and Boreholes

Salinity of water in shallow aquifers can be affected by upward movement of brines by leakage within wells and boreholes. Data presented by Core Laboratories, Inc., (1972a) indicate the mean depth to brine is about 5,000 ft, and the minimum and maximum depths are 208 and 20,000 ft, respectively. Potentially, brines can move toward the surface through unplugged deep boreholes that have been drilled through or into several deep aquifers throughout the study area in search for oil and gas.

Leakage also may occur through deep water wells. Marshall (1976) reported that many water wells were drilled to depths of as much as 500 ft in an area west of San Angelo during a drought in the 1950's. He further reported that many of the wells were abandoned unplugged after they produced saline water. However, Richter and others (1987) concluded that these water wells were not a major source of leakage of brine. A search of hundreds of drillers' logs of water wells in the area did not locate many deep wells or evidence of saline water in those wells.

The importance of properly casing, cementing, and plugging deep boreholes can be inferred from figure 20. Casing keeps unwanted soils and fluids out of the borehole and retards the movement of liquids and gas between formations. Cementing around casing prevents or reduces leakage between the borehole and casing. Cementing frequently is used at the top of high-pressure brine formations to prevent upward vertical movement of that water and at the top and base of shallow aquifers to minimize contamination from leakage along the outside of casings. Plugging abandoned boreholes and cased wells can prevent vertical movement within the borehole or casing if plugging requirements initiated in 1965 are followed.

The first oil and gas wells were drilled in the study area by about 1912. At the end of 1989, the computer files of the Railroad Commission contained entries for 19,361 active oil and gas-related wells and boreholes in the seven major counties of the study area (Susan Rhyne, Railroad Commission of Texas, written commun., 1990). The file included about 12,140 active producing oil wells and 302 active producing gas wells. About 1,400 of the boreholes temporarily were abandoned or shut in. Most of the remaining boreholes were used for disposal, water injection, or other services. The files did not include plugged and abandoned boreholes. The computer files of the Petroleum Information Corp. contained information for 40,178 boreholes in the seven counties as of the end of 1988, including 20,817 plugged boreholes, and for all reported drilling in the study area since 1912. About 67 percent of the reported boreholes and 65 percent of the reported plugged boreholes were in Howard, Mitchell, and Scurry Counties.

About 21,000, or more than one-half of the known boreholes in the seven-county area were drilled before the advent of statewide rules in 1965 that required abandoned boreholes to be plugged, and most of these boreholes were abandoned because of their age. Most of these abandoned boreholes were not cased, cemented, completed, or plugged according to current rules and could provide leakage from brine aquifers to shallow aquifers. A large percentage of cased boreholes older than 20 years can leak brine to shallow aquifers. Casing will last only a few years in some areas because of the corrosive properties of local deep-aquifer brines. In most areas of the State, 20 years is the life expectancy of casing (Morrow and others, 1987). Of the boreholes recorded by the Petroleum Information Corp. in the study area, 22,713 or 57 percent, are more than 20 years old, and 16,351, or 41 percent, are more than 30 years old.

An example of a single leaking well contaminating large areas is shown by Reed (1961). He drilled many shallow test boreholes adjacent to a deep abandoned oil-test borehole drilled in 1938, to determine the extent of shallow saline-water contamination from brine leakage through the abandoned borehole (Reed, 1961, p. 16). He determined that about 400 to 600 acres of fresh ground water had been "adversely affected" since the well had been abandoned 22 years earlier.

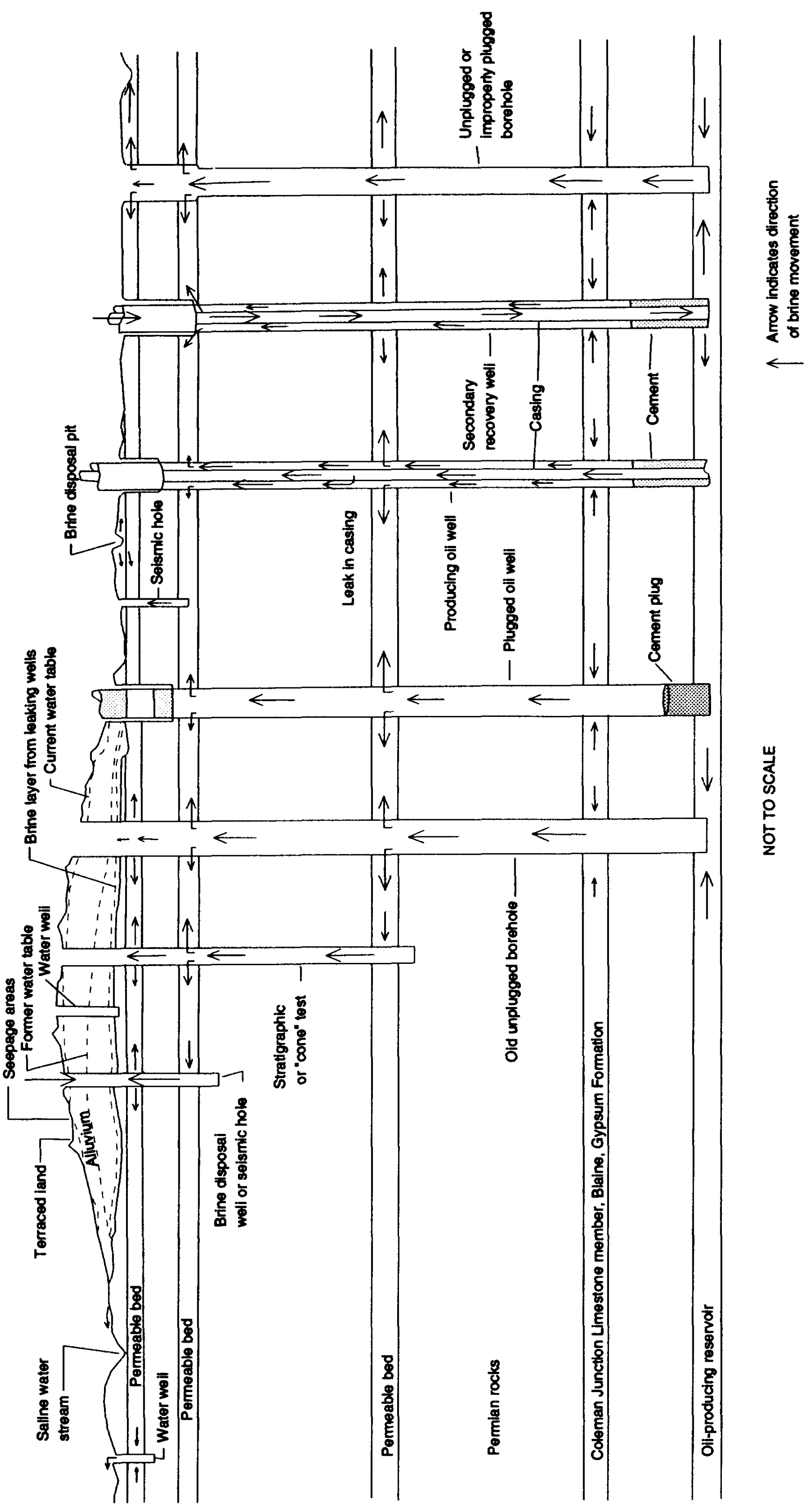


Figure 20. Conceptual diagram showing potential brine movement. (Modified from Texas Energy and Natural Resources Advisory Council, 1983.)

Disposal of Brines Associated With Oil and Gas Production

Brines enter the surface and shallow subsurface as a result of leakage during pumping, storage, transmission, and disposal. The quantity of brine associated with oil and gas production varies between wells and with time. The brines were separated from the hydrocarbons, and then disposed of at the surface into pits (lined and unlined), with lesser quantities routed to drainage channels and into the subsurface through disposal wells and secondary-recovery (injection) wells. Small quantities of brine also have been disposed of by irrigation or evaporation from metal tanks. The discussion in this section is limited to disposal into pits and through disposal wells and secondary-recovery wells.

The volume of brine produced increases with the age of the field, as production of oil and gas decreases. Using 4 years of data, the total brine production was compared to oil production for those years so that temporal changes in the volume of brine produced with each barrel of oil could be determined. The ratios of brine production to oil production in the seven major counties for 1957, 1961, 1967, and 1983 were 0.60, 0.95, 2.1, and 6.5, respectively.

Data and information related to currently permitted disposal and injection wells are stored in computer files by the Underground Injection Control Section of the Railroad Commission. As of 1989, there were about 4,700 such wells in use in the seven major counties of the study area (Bill Renfro, Railroad Commission of Texas, oral commun., 1989). The files included monthly disposal volumes of brine for each of the permitted disposal and secondary-recovery wells for selected periods during 1982-84. Except for 1957, 1961, and 1967 inventories conducted by the Railroad Commission of Texas (1982) in cooperation with the Texas Water Commission (1963), these data represent the only known disposal and injection data. Total brine disposal and injection by county for 1983 and for the 1957, 1961, and 1967 inventories are presented in table 5 for the seven major counties and two minor counties in the study area that had brine disposal. Some of the 1967 data contained sufficient detail to calculate totals for the parts of counties in the study area.

Pits

The purpose of disposing brines into pits was to reduce the quantity of brine by evaporation. Evaporation, however, was often retarded by oil films or stagnation from microorganisms on the surface of the brines. Also, the brine residue accumulated as salt in the pits. Much of the brine in unlined pits infiltrated to the shallow subsurface where it entered local ground water, or moved along lateral bedding planes and discharged as seeps into topographically low areas, or entered water wells (fig. 20). The bottoms of many of the unlined pits are in permeable soils that allow brine movement to the subsurface. Numerous studies have documented infiltration of brines from pits into local water sources (Livingston and Bennett, 1944; Shamburger, 1959; Reed, 1961; Crouch and Burnitt, 1965; Richter and others, 1990).

Use of lined and unlined pits for disposal of brines began with the development of oil production in the study area in 1912. Most of the brines from early production was disposed of in pits, with some disposal to drainage channels. About 40 percent of the disposal of brine in 1957 was to the surface, mostly into pits. The mean dissolved-solids concentration of all samples in the brine analyses file was 102,000 mg/L. Therefore, the dissolved solids disposed of into pits in 1957 represented 972 ton/d, about 2.5 times the mean-daily dissolved solids discharged from the study area at station 08136700 during 1969-86 (fig. 6).

By 1961, 16 percent of the inventoried disposal was to pits. However, by then, brine from pits had affected surface and shallow-aquifer water, which resulted in efforts to minimize this practice in many areas. By 1967, only about 2 percent of disposal of brine within the study area was to pits, and in 1969, the Railroad Commission issued a statewide ban on pit disposal; the practice no longer is legal. Although illegal for disposal purposes, pits continue to be used during drilling and production of oil and gas for temporary storage of brines, drilling muds, and fluids.

More than 1,000 pits probably have been used for brine disposal in the study area. Much local brine infiltration in areas surrounding pits is expected for many years, because of the slow transport properties of most local soils. The present and future extent of the effect of brine infiltration is a function of many local characteristics including the volume and salinity of disposed brines, the permeability of the soils adjacent to the pits, the gradients of the land and water table, and the quantities of precipitation and runoff available to transport the salt loads.

Table 5. Brine disposal and injection by counties, 1957, 1961, 1967, and 1983

[--, unknown; <, less than]

County	Year	Surface disposal		Subsurface injection					
		Total		Disposal wells		Secondary-recovery wells		Total	
		Thousands of barrels	Percent	Thousands of barrels	Percent	Thousands of barrels	Percent	Thousands of barrels	Percent
Coke	1957	654	24	2,059	76	0	0	2,059	76
	1961	263	7	--	--	--	--	3,434	93
	1967	110	1	1,103	8	13,300	92	14,403	99
	1983	0	0	351	4	7,848	96	8,199	100
Coleman	1957	718	45	167	11	705	44	872	55
	1961	324	3	--	--	0	0	9,376	97
	1967	[1]600	100	[1]0	0	[1]0	0	[1]0	0
	1983	0	0	694	14	4,338	86	5,032	100
Concho	1957	40	100	0	0	0	0	0	0
	1961	22	43	--	--	--	--	29	57
	1967	[1]1	6	--	--	--	--	[1]15	94
	1983	0	0	21	36	37	64	58	100
Howard	1957	10,562	37	7,655	27	10,045	36	17,700	63
	1961	4,378	15	--	--	--	--	24,924	85
	1967	327	1	5,470	26	24,338	73	32,889	99
	1983	0	0	5,470	9	53,057	91	58,527	100
Mitchell	1957	515	100	0	0	0	0	0	0
	1961	892	69	--	--	--	--	406	31
	1967	67	3	434	22	1,451	74	1,885	97
	1983	0	0	513	2	21,733	98	22,246	100
Runnels	1957	889	18	3,344	68	686	14	4,030	82
	1961	199	3	--	--	--	--	7,477	97
	1967	22	<1	2,496	26	7,256	74	9,752	100
	1983	0	0	1,446	30	3,450	70	4,896	100
Scurry	1957	5,087	50	3,872	38	1,276	12	5,148	50
	1961	3,755	31	8,477	69	11	<1	8,488	69
	1967	[2]355	2	[3]8,938	60	[3]5,576	38	[4]14,514	98
	1983	0	0	2,669	1	271,338	99	274,007	100
Sterling	1957	705	100	0	0	0	0	0	0
	1961	333	58	--	--	--	--	460	42
	1967	[1]1	1	--	--	--	--	[1]86	99
	1983	0	0	674	37	1,161	63	1,835	100
Tom Green	1957	679	72	259	28	0	0	259	28
	1961	632	42	--	--	--	--	881	58
	1967	[1]6	2	--	--	--	--	[1]339	98
	1983	0	0	497	25	1,513	75	2,010	100

Footnotes at end of table.

Table 5. Brine disposal and injection by counties, 1957, 1961, 1967, and 1983--Continued

Total disposal and secondary recovery in the study area (thousands of barrels)			
Year	Surface	Subsurface	Total
1957	19,849	30,068	49,917
1961	10,798	55,475	66,273
1967	[1]1,191	[1]67,606	[1]68,797
1983	0	376,810	376,810

[1] Total for part of county or counties in study area.

[2] 57 for part of county in study area.

[3] Unknown for part of county in study area.

[4] 8,237 for part of county in study area.

Disposal Wells

Many disposal wells in the study area inject brine into formations immediately below shallow aquifers. Hence, large pressures at injection points could cause upward movement of brines that affect water in shallow aquifers. Also, brines could be transported naturally if water pressures and formation permeabilities allowed the movement, or they could be transported through boreholes that are not adequately cased, cemented, or plugged. Improper completion of disposal wells or deterioration of casing from corrosion therefore could be a source of brine leakage to shallow aquifers.

As of March 1987, about 184 brine-disposal projects were issued permits by regulatory agencies within the seven major counties of the study area. Each project included one to several hundred disposal wells. Permitted disposal rates for each project ranged from about 100 to about 10,000 bbl/d (Railroad Commission of Texas, written commun., 1987). The maximum-daily disposal rates are available for most of the permitted projects, whereas the mean rates are available for only about one-half of the projects. On the basis of available data, an estimated 112,000 bbl/d, or about 40.9 million bbl of brine were disposed of through disposal wells in 1987 in the seven major counties. This is larger than the total disposal of about 11 million bbl reported in 1983 for those counties (table 5).

Much brine has been injected into the Coleman Junction Limestone, a member of the Putnam Formation. The disposal of brine by injection into the Coleman Junction Limestone requires excessive injection pressures to overcome the hydrostatic pressure within the geologic member. A Railroad Commission internal memorandum dated August 15, 1977, indicated that only five wells were then injecting brine into the Coleman Junction Limestone in Runnels County. In this memorandum, the District 7-C Director requested that permits for these wells be rescinded because of the possible effects on freshwater. All such injection operations apparently have since been discontinued (Texas Energy and Natural Resources Advisory Council, 1983).

Secondary-Recovery Wells

Secondary-recovery wells have been used for brine injection in the study area since about 1955; the practice has increased so that currently most of the produced brine is disposed of by this method. Injection of brine through secondary-recovery wells for the seven major counties in 1983 was about 359 million bbl, compared to about 11 million bbl for disposal wells and no reported disposal to pits (table 5). Railroad Commission computer files indicate 2,742 injection wells used in secondary recovery were in operation in the seven major counties of the study area at the beginning of 1990. Injection and pressure data and information on each permitted secondary-recovery project in the State are published every 2 years by the Railroad Commission of Texas. The 1982 report indicated that there were 188 active permitted projects in 1982 and 43 projects discontinued since 1968. Although more recent data are available for secondary-recovery projects (projects begun since 1982) in files at the Railroad Commission, the data have not been published.

Many of the projects had brine hydrostatic levels within a few hundred feet of the corresponding water-level altitude before secondary recovery was initiated. In many cases the hydrostatic levels were higher than the water-level altitude and in some cases were above land surface. Upward vertical movement of brines at each of these projects with high hydrostatic levels potentially could contaminate streamflow or shallow-aquifer water, particularly where movement can occur through improperly cased, cemented, or plugged wells proximate to those projects.

Four of the six projects that had hydrostatic levels above the land surface in oil fields were near the Colorado River (Railroad Commission of Texas, 1982). About 143 million bbl of brine had been injected at these six projects as of 1982. The largest volume of disposal for these sites, about 87 million bbl, was at a site adjacent to E.V. Spence Reservoir in the I.A.B. Field (pl. 6). The hydrostatic level at this site in 1982 was 392 ft higher than the original level and 76 ft above land surface. The specific-gravity adjusted level of the brine reservoir in 1982 was 76 ft above land surface. Thus, injection at this site poses a potential for brine intrusion to E.V. Spence Reservoir that is much greater than occurs naturally.

Reported data for the secondary-recovery projects indicate that only a few projects indicated possible migration of brine to the shallow subsurface or the land surface. The latest reservoir pressure exceeded the original pressure for only 4 of the 148 projects that reported both pressures; thus, injection rarely caused reservoir pressures to exceed natural pressures. Also, brine movement could occur at or adjacent to only a few projects. For example, original brine hydrostatic levels exceeded shallow ground-water levels at only 13 percent of the projects with reported data, but 51 percent of the total volume of injected brine, as of 1982, was at those projects. Because many of the projects with high original and latest hydrostatic levels are proximate to the Colorado River and tributaries, brine leakage from these projects could contaminate shallow-aquifer water or discharge as seeps at topographically low areas and move to the Colorado River.

Many cases of brine leakage to the surface from secondary-recovery wells are documented in the study area. One example of such a case was reported by the U.S. Army Corps of Engineers (1980) in the Sharon Ridge Field just south and east of the Colorado River and near the Scurry-Mitchell County line. Water from a spring at this location was flowing 10 gal/min and had large chloride concentrations (53,000 mg/L). An injection well at the head of the small tributary, about 200 ft from the spring and about 50 ft higher in elevation, was pumping brine down the well at about the same rate. The inorganic-chemical characteristics of the spring water was similar to that of the oil-field brine, further linking the spring to the injection well.

Ground-Water Discharge Through Saline Soils

In the seven major counties of the study area, saline soils underlie about 123,400 acres, or 3 percent of the land surface. About 90,130 acres, or 73 percent of this total, is associated with oil and gas production. The area in acres, by source of saline water, for the seven major counties (Texas State Soil and Water Conservation Board, 1985) is as follows:

County	**Dryland saline seeps (acres)**				**Saline soils (acres)**			
					Natural			
	Irrigated cropland	**Unirrigated cropland**	**Pasture**	**Range**	**Dryland**	**Alluvial**	**Associated with oil and gas production**	**Total**
Coke	0	0	0	0	0	0	2,900	2,900
Concho	0	305	701	500	0	0	0	1,506
Howard	200	50	0	15	12,980	0	82,700	95,945
Mitchell	0	6,200	150	200	0	0	300	6,850
Runnels	50	2,900	3,500	700	0	0	920	8,070
Scurry	0	1,500	100	2,000	0	600	2,700	6,900
Tom Green	0	0	20	24	0	582	610	1,236
Totals	250	10,955	4,471	3,439	12,980	1,182	90,130	123,407

The appearance of saline seeps in dryland areas in the western part of Texas is a recent occurrence (U.S. Soil Conservation Service, 1983). Some dryland seeps appeared by 1930 and were widespread after 1950 in most of the affected counties. Surveys by the SCS identified 11,240 acres of seeps in 1978 (Neffendorf, 1978), 15,200 acres in 1983 and 19,100 acres in 1985 (U.S. Soil Conservation Service, 1983 and 1985). A total of 434 seeps was identified in the 1983 survey, thus the mean size of the seeps was about 35 acres.

Ground-water discharge (seeps) through saline soils is a probable cause of increased salinity of streamflow and shallow-aquifer water. Saline water supports growth of salt cedar and other salt-tolerant phreatophytes and grasses in abandoned fields formerly planted with cotton and other local nonsalt-tolerant crops. Seeps therefore pose financial burdens to farmers because of lost revenues from crops and because of devaluation of lands. Consequently the U.S. Soil Conservation Service (1983) attempted to identify the sources of the seeps using data from 39 counties in west Texas, including the entire study area. The SCS determined that the relation of seeps to soil types could not be correlated. Most of the seeps were on sloping landscapes, but only 18 percent were in low areas. Farming practices, particularly terracing, commonly are blamed for the seeps, but only 39 percent were in terraced fields. A comparison, by county, of the number and acreage of saline seeps with the extent of terraces showed no correlation between saline seeps and terraces. The preceding table shows that 10,955 acres of the 19,115 acres of seep-covered land within the seven counties were on cropland. Cropland covered only 40 percent of the study area but contained 57 percent of the saline seeps.

Because increases in mean-annual precipitation generally cause higher water levels, which are assumed to contribute to saline seeps, the long-term annual precipitation for the study area was reviewed to determine if recent precipitation exceeded historical precipitation. Data for 9 precipitation gages with more than 40 years of record, as of 1986, were reviewed. The longest period of record was 100 years, the shortest was 41 years, and the mean was 75 years.

The mean-annual precipitation prior to 1960 was 20.10 in., compared to 23.40 in. for 1969-86 (fig. 5). Thus, the mean-annual precipitation for 1969-86 exceeded that prior to 1960 by 3.30 in., or 16 percent. The water-level rises associated with the precipitation increases may result in an increase in salinity by increasing the availability of dissolved solids through mineral dissolution. Evapotranspiration during 1969-89 probably exceeded evapotranspiration in prior years based on the precipitation records. However, because the depth to water exceeded 10 ft (pl. 4) throughout most of the study area, precipitation increases probably did not contribute to major regional increases in salinity of soils resulting from evapotranspiration.

The geologic groups with the largest percentage of seeps are the Clear Fork, 35 percent; the Cisco, 23 percent; and the Dockum, 15 percent. The remaining 27 percent are in 19 formations or groups in 4 systems, with less than 6 percent each. About 66, 17, and 15 percent of the seeps are in outcrops of the Permian, Quaternary, and Triassic Systems, respectively, and the other 2 percent are in the Cretaceous and Tertiary Systems. Although only 17 percent of the seeps are in the Quaternary System, about 75 percent of them are in soils that have developed on outwash, windblown, and alluvial materials of Quaternary age. This difference is attributed to differences between soils mapping and geologic mapping. Geologic mapping includes the large areas of deeper Quaternary deposits over the Cretaceous, Triassic, and Permian rocks, while the soils mapping also includes all of the thin fringe deposits. The saline seeps are on the fringes of these major deposits where the materials thin out over the underlying, less permeable shales, sandstones, and other rocks.

A 1986 inventory by the SCS (U.S. Soil Conservation Service, written commun., 1987) identified about 155 saline seeps in Runnels County, whereas, 92 were identified in the 1983 report (U.S. Soil Conservation Service, 1983). Most seeps in Runnels County are in sloping or topographically low areas near streams. The specific conductance of many seeps has been measured by the SCS. Dissolved-solids concentrations estimated from specific-conductance measurements show that few seeps have concentrations of less than 1,000 mg/L. Most concentrations are between 1,000 and 10,000 mg/L with some concentrations as large as 20,000 to 40,000 mg/L (U.S. Soil Conservation Service, written commun., 1987). The data for sites with multiple samples indicate that the salinity of the seeps changes with hydrologic conditions.

RELATION OF SALINITY CLASSIFICATION TO OIL AND GAS PRODUCTION

The possibility of a relation between water samples classified as "brine" by salt-norm analysis and proximity of the sampling sites to oil and gas production was evaluated (table 6). Proximity of a site to an oil and gas field was defined on the basis of whether the sample source was: (1) within about 1 mi of a mapped oil and gas field (pl. 6) (Midland Map Co., 1986; Heydrick Map Services, 1986) or (2) outside these limits. Salt-norm classifications of HS-mixed and brine-mixed could indicate the importance of natural sources of chloride in salinity development. The frequency of other salt-norm classifications was not related to the proximity of a water source to oil and gas fields.

Ratios of Br/Cl were useful in this study to distinguish among potential sources of chloride in water when chloride concentrations were greater than about 1,000 mg/L. The chloride in 19 of the 121 samples (including 9 streamflow samples not included in fig. 15) for which bromide and chloride concentrations were determined was classified as originating from water from Pennsylvanian System deep aquifers (fig. 15, table 7). Fifteen of these nineteen samples were from wells within 1 mi of a producing oil and gas field (table 7). Of these 15 samples, 14 were from wells proximate to oil and gas fields producing from Pennsylvanian System formations. A few samples, 3 of 13, that were classified as similar to Permian System brine, were proximate to oil and gas fields producing from Permian System formations. Some water samples had a classified source of chloride that was different from that of the producing formations in adjacent oil and gas fields, possibly because of leakage from cased, nonproducing zones of deep aquifers that are penetrated by boreholes or casings. For this reason, shallow-aquifer water might be influenced by Permian System brine even though local oil and gas are produced from Pennsylvanian or Ordovician deep aquifers.

A substantial number of analyses (37 of 121) could not be classified using the Br/Cl mixing curve diagrams (table 7). These analyses had chloride concentrations that were less than about 1,000 mg/L (table 4). The proportion of analyses having an "unknown" source of chloride was less for the group of analyses with nitrate determinations (fig. 15). The Cl/NO_3 equivalent ratios were useful in classifying the predominance of chloride related to soil-mineral dissolution, even at chloride concentrations of less than 1,000 mg/L (table 4).

Table 6. Distribution of samples by proximity to oil and gas fields in the upper Colorado River Basin, Texas, grouped by salt-norm analysis classifications of the principal sources of saline water

Principal source of saline water[1]	Number of samples in classification	Number of samples for which site is proximate to an oil and gas field[2]	Number of samples for which site is not proximate to an oil and gas field[2]
Meteoric-CO_3	3	1	2
Gypsum or meteoric-SO_4	37	23	14
HS-mixed	5	2	3
Brine-mixed	22	10	12
Brine	19	14	5
Total number of sites	86	50	36

[1] Salt-norm classifications of the source of saline water (Bodine and Jones, 1986): Meteoric norms derive solutes from weathering and dissolution of carbonate (meteoric-CO_3) and sulfate (meteoric-SO_4) minerals. Meteoric-CO_3 norms are dominated by carbonate normative minerals. Meteoric-SO_4 norms are dominated by sodium, magnesium, and potassium sulfate normative minerals. Marine norms classified in this study include water that derives salinity from dissolution of anhydrite or gypsum (gypsum), halite (brine), or by evaporative concentration or mixing with deep-aquifer brines (HS-mixed). Gypsum and brine norms are dominated by normative anhydrite and normative halite salts, respectively. HS-mixed norms contain more than 12 percent of the sum of normative bischofite and carnallite salts. Diagenetic norms (brine-mixed) include more than 5 percent of the sum of normative antarcticite and normative tachyhydrite. A brine-mixed norm is characteristic of deep-aquifer brines with the cation composition modified by reactions with shallow-aquifer minerals.

[2] Site is defined as proximate to an oil and gas field if within 1 mile of the field. Oil- and gas-field boundaries are taken from (1) plate 6 and (2) Midland Map Co., 1986 (Coke, Concho, Howard, Mitchell, Scurry, and Tom Green Counties) and Heydrick Map Services, 1986 (Runnels County).

Table 7. Distribution of samples by proximity to oil and gas fields in the upper Colorado River Basin, Texas, grouped by trace-species/chloride ratio classifications of the principal sources of chloride

[--, not applicable to source of chlorinity classification]

Source of chloride	Number of samples in classification	Number of samples for which site is proximate to an oil and gas field[1]	Number of samples with same classification as oil-producing system	Number of samples for which site is not proximate to an oil and gas field[1]
Mixing with halite dissolution brine	8	6	--	2
Mixing with water from Pennsylvanian System deep aquifers	19	15	14	4
Mixing with water from Permian System deep aquifers	13	7	3	6
Mixing with water from Pennsylvanian System and Permian System deep aquifers	16	7	--	9
Mixing with water from Permian System deep aquifers and halite dissolution brine	9	7	5 (Permian System oil or gas production)	2
Dissolution of unsaturated-zone minerals	19	9	--	10
Mixing with water from an unknown source of chloride	37	26	--	11
Total number of sites	121	77		44

[1] Site is defined as proximate to an oil and gas field if within 1 mile of the field. Oil- and gas-field boundaries are taken from (1) plate 6 and (2) Midland Map Co., 1986 (Coke, Concho, Howard, Mitchell, Scurry, and Tom Green Counties) and Heydrick Map Services, 1986 (Runnels County).

The classifications of the processes affecting the salinity of water in this report were tentative and were not verified by site-specific hydrogeologic and geochemical studies. More comprehensive areal sampling and analyses of trace species in deep-aquifer brines, in freshwater and slightly saline water, and in soluble soil salts, and the collection and analysis of duplicate samples would improve the reliability of the classification.

SUMMARY

The upper Colorado River and some of its tributaries between Lake J.B. Thomas and O.H. Ivie Reservoir contain water having dissolved-solids concentrations greater than 1,000 mg/L. The discharge-weighted mean dissolved-solids concentrations for 1969-86 exceeded 1,000 mg/L in water at four of the five water-quality stations upstream from E.V. Spence Reservoir. The largest long-term discharge-weighted mean dissolved-solids concentration of streamflow was 2,220 mg/L for Beals Creek (station 08123800). The concentration for the Colorado River just upstream from E.V. Spence Reservoir (station 08123850) was 1,320 mg/L and for the Colorado River at station 08136700, just downstream from O.H. Ivie Reservoir, was 686 mg/L. Dissolved-solids concentrations of flows in the upper Colorado River generally decreased in the downstream direction. Analyses at nine water-quality stations indicated that dissolved-solids concentrations generally decreased prior to about 1982 in Elm Creek and in the Colorado River upstream from Beals Creek, and increased in Beals Creek.

From 1986 to 1988, dissolved-solids loads increased at all nine stations, probably as a result of near-record precipitation in 1986. The largest increases were in Beals Creek and the Colorado River downstream from Beals Creek resulting from releases of saline water from Natural Dam Salt Lake that contained about 654,000 tons of dissolved solids and had a mean dissolved-solids concentration of 7,900 mg/L. This amount represents about 51 percent of the dissolved-solids load to E.V. Spence Reservoir during 1986-88.

Dissolution of sulfur-bearing minerals was the predominant source of streamflow salinity in the basin as determined by salt-norm analysis. Water samples from Elbow Creek with dissolved-solids concentrations exceeding 1,000 mg/L derived their chloride from Permian System deep aquifers, whereas water from a site on the Colorado River derived its chloride from dissolution of evaporatively concentrated halite from the adjacent river alluvium.

Diversion of low flows at a site on the upper Colorado River beginning in 1968 decreased the dissolved-solids loads of inflow to E.V. Spence Reservoir by about 7 percent while removing only about 3 percent of the total flow. For 1983-85, the dissolved-solids discharge being removed from Beals Creek by diversion might have been comparable to the dissolved-solids discharge being removed from the Colorado River.

Many of the geologic formations composing the shallow aquifers are major sources of freshwater and slightly saline ground water. Water levels measured in 1986 indicated that depths to water were less than 100 ft in most wells of the shallow aquifers and decreased in depth near the major streams. In many wells in Howard, Mitchell, and Runnels Counties, depths to water were less than 10 ft. Gradients of ground-water levels were similar to gradients of surface topography. Recharge was assumed to be infiltration from runoff in the drainage area.

The estimated dissolved-solids concentrations exceeded 500 mg/L for water from about 335 of 386 wells and springs for which specific conductance was measured in 1986. The mean value of the estimated dissolved-solids concentration for water from the 386 wells and springs was about 1,750 mg/L. Water samples from about 233 wells and springs had estimated dissolved-solids concentrations greater than 1,000 mg/L, the recommended secondary constituent level established by the TDH.

Dissolution of halite or mixing with deep-aquifer water was the most common cause of increased salinity in nearly one-half of 77 water samples from shallow aquifers, as classified using salt-norm analysis; the second most common cause was the weathering and dissolution of sulfate minerals (about 42 percent). Mixing with water from soil-mineral dissolution was classified as the principal source of chloride in about 28 percent of 67 water samples from shallow aquifers having nitrate determinations. Trace-species/chloride ratios indicated that mixing with water from deep aquifers in rocks of the Pennsylvanian System was the principal source of chloride in about 24 percent of 45 shallow-aquifer samples lacking nitrate determinations. Water in the Valley alluvial aquifer derived its salinity mainly from dissolution of unsaturated-zone minerals or sulfur-bearing minerals within the saturated aquifer. Analyses of water from one well in the Leona aquifer and three wells open to both the Leona and Clear Fork aquifers indicated that chloride was derived from dissolution of unsaturated-zone minerals. Analyses of water from the Dockum aquifer indicate that the dissolved solids in water samples from about one-half of the wells resulted from dissolution of sulfur-bearing minerals.

Dissolved solids in water from the Whitehorse-San Andres aquifer were classified as being predominantly from dissolution of sulfur-bearing minerals. Two wells in this aquifer, however, contain sufficient chloride to indicate possible mixing with water from Permian or Pennsylvanian System deep aquifers and halite dissolution brine. Analysis of salinity in water from the San Angelo aquifer indicated that dissolved solids originated principally from mixing between shallow-aquifer water and brine from deep aquifers. The analysis of water from the Clear Fork aquifer indicates that the principal source of dissolved solids was the dissolution of unsaturated-zone minerals and sulfur-bearing minerals. A smaller proportion of the dissolved solids was from mixing with water from Pennsylvanian System or Permian System deep aquifers.

Each of the 10 aquifers designated as deep aquifers contains at least one hydrocarbon-bearing formation. As of 1986, about 3 billion bbl of oil had been produced in the seven major counties of the study area. In the lower elevations of the Colorado River valley, the potentiometric surface of the deep aquifers, as of 1965, was above land surface. Oil- and gas-well test data collected between 1965 and 1990 indicated that potentiometric surfaces of deep aquifers generally were lower in 1990 than in 1965.

Chloride constituted more than 90 percent of the ionic equivalent charge and sodium constituted between 70 and 90 percent of the cationic equivalent charge in water from deep aquifers. Calcium, magnesium, and sulfate constituted the remaining equivalent charge. The mean dissolved-solids concentrations of water from eight deep aquifers ranged from 61,200 to 128,000 mg/L. The mean concentration for all analyses was 102,000 mg/L.

Processes affecting the salinity of water in the upper Colorado River Basin included evapotranspiration, dissolution of minerals, mixing with brines, and ground-water discharge through saline soils. Some salinity in streamflow and shallow-aquifer water was attributed to evapotranspiration in areas where shallow-aquifer water was close to land surface, in irrigated areas, and along streams. The evapotranspiration was largely from phreatophytes and was comparable to the mean streamflow from the study area during 1969-86. Evapotranspiration was not considered a regional contributor to the salinity of water in shallow aquifers. Dissolution of sulfur-bearing minerals, such as gypsum and pyrite, in shallow aquifers contributed to salinity because of their presence in soil and shallow-aquifer formations. Dissolution can occur as recharge water moves through soils and as water levels increase in the shallow aquifers.

Mixing with brines associated with oil and gas production is a major process affecting the salinity of streamflow and shallow-aquifer water. There were 40,178 reported oil- and gas-related boreholes as of 1988 in the seven major counties of the study area. Approximately one-half of these boreholes were reported to be plugged and abandoned, most before 1965, when current casing, cementing, completion, and plugging requirements were initiated to protect shallow-aquifer water. Brines can move through abandoned boreholes or improperly cased, cemented, or plugged wells to the surface or shallow subsurface.

The ratio of brine production to oil production in the seven major counties increased from 0.60 to 6.5 between 1957 and 1983. Most brines from early production were disposed of in more than 1,000 pits until 1969, when this practice became illegal. Studies have shown evidence of brine contamination of shallow-aquifer water because of infiltration through the bottoms of pits. For 1987, mean disposal rates were about 112,000 bbl/d by injection through several hundred disposal wells. Disposal into the Coleman Junction Limestone, a member of the Putnam Formation of the Permian System, has been discontinued because of possible effects on freshwater.

Secondary-recovery wells have been used to inject brine in the study area since about 1955; most of the produced brine currently is disposed of by this method. As of 1982 there were about 188 active permitted projects. About 359 million bbl of brine were injected into oil-producing formations in the seven major counties in 1983 compared to about 11 million bbl through disposal wells. Potential hydrostatic heads for the injection wells at some of these projects are higher than the water-level altitude for shallow aquifers or, in some wells, higher than land surfaces. About 143 million bbl of brine had been injected at six such projects as of 1982, four of which are near the Colorado River. The potential for brine intrusion to E.V. Spence Reservoir from one of these sites is much greater than occurs naturally. As of 1990, more than 2,700 injection wells used in secondary recovery were in operation in the seven major counties. Instances of brines leaking to the surface through abandoned wells adjacent to injection projects have been documented.

About 123,400 acres of saline soils were identified in the seven major counties of the study area in 1985, which is about 3 percent of the surface area of those counties. Oil and gas production were the source of 73 percent of the saline soils. The size and number of saline seeps are temporally increasing. The increase may be related to increases in precipitation during 1969-86.

A reaction was noted between water samples classified as brine by salt-norm analysis and proximity of the sites of samples analyzed to areas of oil and gas production. Ratios of Br/Cl in water with greater than 1,000 mg/L of chloride indicated that the sample water might originate from the Pennsylvanian System deep aquifers, and that 15 of 19 samples were within 1 mi of a producing oil and gas field.

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Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989

[--, no data; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Depth to water level below land surface (feet)	Specific conductance (µS/cm)	pH (standard units)
		Streamflow		
Colorado River sites:				
Bull Creek	08-27-87	--	1,510	7.7
Bluff Creek	08-27-87	--	3,940	8.0
Colorado River	08-28-87	--	10,100	8.0
Canyon Creek	08-28-87	--	2,600	7.9
Little Sulphur Creek	08-28-87	--	1,230	7.8
Bone Hollow Creek	08-25-87	--	2,880	7.8
Jayhawk Creek	08-25-87	--	5,980	7.9
Beals Creek site:				
Elbow Creek	08-26-87	--	8,540	7.9
Elm Creek site:				
Coyote Creek	08-27-87	--	2,890	8.1
		Shallow aquifer: Valley alluvial--Ogallala Formation subcrop probable		
28-44-101	08-26-87	4.2	5,530	8.0
	03-06-89	4.6	6,740	--
28-52-103	08-26-87	32.7	2,710	7.7
	03-06-89	37.0	2,950	--
28-52-504	08-26-87	16.0	4,650	7.5
	03-06-89	16.6	--	--
28-52-702	08-26-87	--	8,240	8.6
	03-06-89	--	--	--
		Shallow aquifer: Valley alluvial--Dockum Group subcrop probable		
28-32-208	08-27-87	94.5	5,450	6.8
	03-06-89	94.4	5,290	--
28-32-503	08-28-87	82.2	4,040	8.3
28-32-603	08-27-87	86.5	3,920	7.1
	03-06-89	89.5	4,050	--
		Shallow aquifer: Valley alluvial--Guadalupe Series subcrop probable		
29-59-701	08-31-87	15.0	1,980	8.4
	02-01-89	14.5	3,170	--

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Depth to water level below land surface (feet)	Specific conductance (μS/cm)	pH (standard units)
Shallow aquifer: Valley alluvial--Clear Fork Group subcrop probable				
42-02-102	08-26-87	11.0	3,200	7.3
Shallow aquifer: Dockum				
28-24-503	08-27-87	79.5	3,200	8.2
	03-07-89	70.0	3,270	--
28-24-704	08-27-87	126.0	5,750	8.2
28-24-805	08-27-87	64.5	4,040	7.5
	03-07-89	65.0	3,640	--
28-32-906	08-27-87	57.1	4,470	7.2
	03-06-89	60.6	8,350	--
28-40-312	08-25-87	56.3	4,450	7.3
	03-07-89	57.5	4,860	--
28-40-602	08-25-87	15.3	4,200	7.4
	03-07-89	19.1	4,180	--
28-45-301	08-27-87	108.5	3,620	7.6
	03-06-89	108.5	3,600	--
28-48-901	08-25-87	24.3	6,450	7.9
	03-07-89	8.2	6,510	--
28-54-304	08-26-87	21.6	2,460	7.4
	03-07-89	22.6	3,110	--
28-54-305	03-07-89	--	10,500	--
28-55-101	08-26-87	16.4	16,500	7.6
	03-07-89	18.1	15,600	--
29-17-505	08-27-87	--	5,020	7.6
29-25-707	08-28-87	38.7	6,560	7.1
29-26-401	08-28-87	18.7	3,690	7.3
29-33-202	08-25-87	37.0	3,660	6.4
29-33-206	03-06-89	--	2,440	--
29-41-705	08-25-87	20.5	15,300	7.3
	03-07-89	23.9	6,070	--
Shallow aquifer: Whitehorse-San Andres				
29-50-603	08-25-87	34.4	5,390	7.4
	03-06-89	41.3	4,540	--
29-51-701	08-25-87	91.5	7,700	7.3
	03-06-89	97.4	8,020	--

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Depth to water level below land surface (feet)	Specific conductance (µS/cm)	pH (standard units)
Shallow aquifer: Whitehorse-San Andres--Continued				
29-58-611	08-31-87	55.0	6,790	8.1
	02-01-89	54.0	7,010	--
29-59-505	08-31-87	50.4	3,400	7.8
	02-01-89	48.2	4,680	--
29-60-803	08-31-87	70.2	2,700	7.4
	02-01-89	71.5	3,730	--
43-03-904	08-31-87	31.1	3,910	7.2
	02-01-89	29.6	3,890	--
43-05-302	09-02-87	32.1	3,350	8.2
	01-31-89	30.6	2,530	--
Shallow aquifer: San Angelo				
43-05-502	09-01-87	59.5	9,150	7.9
	02-01-89	55.9	8,850	--
43-06-301	09-02-87	30.1	5,700	8.8
	01-31-89	30.0	5,510	--
43-13-304	09-01-87	46.0	6,430	8.3
	01-31-89	34.1	5,320	--
43-13-602	01-31-89	--	6,680	--
43-13-603	09-01-87	101.0	5,480	8.2
	01-31-89	97.5	5,480	--
43-14-102-spring	09-01-87	--	15,700	--
	01-31-89	--	14,200	7.7
43-14-609	02-23-89	--	3,360	--
43-37-704	08-26-87	21.7	6,960	6.9
Shallow aquifer: Clear Fork				
42-02-701	08-26-87	9.6	4,530	7.8
42-09-501	09-04-87	36.5	6,040	7.1
43-06-802	09-02-87	24.0	5,050	7.2
	01-31-89	20.0	4,980	--
43-24-501	09-02-87	8.7	4,230	7.2
43-24-802	08-26-87	31.5	8,780	6.8
43-40-601	08-25-87	15.7	--	7.0

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Depth to water level below land surface (feet)	Specific conductance (μS/cm)	pH (standard units)
Deep aquifer: Wolfcamp--Permian System				
Coleman Junction Limestone oil well	08-26-87	--	82,500	5.6
Deep aquifer: Strawn--Pennsylvanian System				
SSR oil well	08-27-87	--	138,000	6.1
Veribest oil well	08-27-87	--	125,000	6.5

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Alkalinity, total, field value (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L)
Streamflow							
Colorado River sites:							
Bull Creek	08-27-87	78	21	180	5.4	82	110
Bluff Creek	08-27-87	270	87	420	6.5	200	820
Colorado River	08-28-87	220	88	1,900	10	140	970
Canyon Creek	08-28-87	180	84	280	5.3	160	620
Little Sulphur Creek	08-28-87	55	26	160	6.2	110	320
Bone Hollow Creek	08-25-87	190	100	300	4.6	300	840
Jayhawk Creek	08-25-87	420	310	590	9.5	130	2,300
Beals Creek site:							
Elbow Creek	08-26-87	280	260	1,200	30	200	1,200
Elm Creek site:							
Coyote Creek	08-27-87	190	110	280	5.0	200	640
Shallow aquifer: Valley alluvial--Ogallala Formation subcrop probable							
28-44-101	08-26-87	64	130	1,100	22	660	1,300
	03-06-89	--	--	--	--	--	--
28-52-103	08-26-87	550	66	46	24	96	1,700
	03-06-89	--	--	--	--	--	--
28-52-504	08-26-87	150	200	550	17	270	790
	03-06-89	4,840	--	--	--	--	--
28-52-702	08-26-87	210	330	1,100	110	150	1,700
	03-06-89	11,200	--	--	--	--	--

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Alkalinity, total, field value (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L)
Shallow aquifer: Valley alluvial--Dockum Group subcrop probable							
28-32-208	08-27-87	680	420	210	7.0	500	2,600
	03-06-89	--	--	--	--	--	--
28-32-503	08-28-87	400	400	150	14	57	2,600
28-32-603	08-27-87	350	110	530	5.2	330	2,000
	03-06-89	--	--	--	--	--	--
Shallow aquifer: Valley alluvial--Guadalupe Series subcrop probable							
29-59-701	08-31-87	140	100	170	3.7	110	960
	02-01-89	--	--	--	--	--	--
Shallow aquifer: Valley alluvial--Clear Fork Group subcrop probable							
42-02-102	08-26-87	350	140	230	4.3	280	1,100
Shallow aquifer: Dockum							
28-24-503	08-27-87	17	4.8	670	2.4	470	270
	03-07-89	--	--	--	--	--	--
28-24-704	08-27-87	26	12	1,200	4.5	340	400
28-24-805	08-27-87	150	71	660	3.3	350	720
	03-07-89	--	--	--	--	--	--
28-32-906	08-27-87	520	130	390	5.0	230	1,800
	03-06-89	--	--	--	--	--	--
28-40-312	08-25-87	340	330	330	10	250	2,500
	03-07-89	--	--	--	--	--	--
28-40-602	08-25-87	210	280	360	8.2	270	1,600
	03-07-89	--	--	--	--	--	--
28-45-301	08-27-87	140	58	550	9.7	98	630
	03-06-89	--	--	--	--	--	--
28-48-901	08-25-87	46	79	1,400	3.0	470	1,400
	03-07-89	--	--	--	--	--	--
28-54-304	08-26-87	180	41	250	3.9	220	280
	03-07-89	--	--	--	--	--	--
28-54-305	03-07-89	--	--	--	--	--	--
28-55-101	08-26-87	1,500	340	1,600	31	64	740
	03-07-89	--	--	--	--	--	--
29-17-505	08-27-87	220	140	680	10	210	1,100
29-25-707	08-28-87	580	160	520	7.9	200	350

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Alkalinity, total, field value (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L)
			Shallow aquifer: Dockum--Continued				
29-26-401	08-28-87	330	110	360	4.0	220	1,300
29-33-202	08-25-87	230	130	170	14	85	280
29-33-206	03-06-89	--	--	--	--	--	--
29-41-705	08-25-87	490	760	2,000	32	310	4,700
	03-07-89	--	--	--	--	--	--
			Shallow aquifer: Whitehorse-San Andres				
29-50-603	08-25-87	580	250	260	6.4	170	1,700
	03-06-89	--	--	--	--	--	--
29-51-701	08-25-87	310	83	1,500	10	36	4,200
	03-06-89	--	--	--	--	--	--
29-58-611	08-31-87	810	150	580	6.0	88	1,800
	02-01-89	--	--	--	--	--	--
29-59-505	08-31-87	120	88	470	20	130	590
	02-01-89	--	--	--	--	--	--
29-60-803	08-31-87	540	110	69	3.5	140	1,500
	02-01-89	--	--	--	--	--	--
43-03-904	08-31-87	620	180	210	3.6	240	2,000
	02-01-89	--	--	--	--	--	--
43-05-302	09-02-87	210	190	300	17	160	1,400
	01-31-89	--	--	--	--	--	--
			Shallow aquifer: San Angelo				
43-05-502	09-01-87	16	52	2,200	41	440	4,100
	02-01-89	--	--	--	--	--	--
43-06-301	09-02-87	290	250	610	14	75	840
	01-31-89	--	--	--	--	--	--
43-13-304	09-01-87	640	330	580	24	72	2,900
	01-31-89	--	--	--	--	--	--
43-13-602	01-31-89	--	--	--	--	--	--
43-13-603	09-01-87	110	100	980	24	240	570
	01-31-89	--	--	--	--	--	--
43-14-102-spring	09-01-87	640	390	2,100	23	420	2,200
	01-31-89	--	--	--	--	--	--
43-14-609	02-23-89	--	--	--	--	--	--
43-37-704	08-26-87	510	140	830	4.9	390	890

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Alkalinity, total, field value (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L)
Shallow aquifer: Clear Fork							
42-02-701	08-26-87	180	190	560	0.70	320	580
42-09-501	09-04-87	450	340	450	1.9	380	1,100
43-06-802	09-02-87	390	360	470	19	260	2,500
	01-31-89	--	--	--	--	--	--
43-24-501	09-02-87	260	200	400	3.8	280	1,000
43-24-802	08-26-87	870	300	680	4.8	240	1,200
43-40-601	08-25-87	800	250	800	61	200	2,200
Deep aquifer: Wolfcamp--Permian System							
Coleman Junction Limestone oil well	08-26-87	1,600	850	20,000	59	4.0	3,900
Deep aquifer: Strawn--Pennsylvanian System							
SSR oil well	08-27-87	9,600	1,400	59,000	230	54	180
Veribest oil well	08-27-87	6,500	1,100	37,000	360	59	1,100

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iodide, dissolved (mg/L)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrate plus nitrate, dissolved (mg/L as N)	Boron, dissolved (µg/L)	Organic carbon, total (mg/L as C)
Streamflow										
Colorado River sites:										
Bull Creek	08-27-87	340	0.30	5.0	--	3.3	792	--	130	13
Bluff Creek	08-27-87	870	.60	30	--	16	2,610	--	410	7.3
Colorado River	08-28-87	2,900	.40	1.5	--	6.2	6,180	--	450	11
Canyon Creek	08-28-87	450	.60	1.7	--	9.6	1,730	--	360	5.8
Little Sulphur Creek	08-28-87	120	.80	.48	--	9.0	762	--	360	10
Bone Hollow Creek	08-25-87	310	2.0	4.4	--	36	1,970	--	490	4.5
Jayhawk Creek	08-25-87	920	1.7	5.0	--	7.7	4,640	--	1,200	10

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iodide, dissolved (mg/L)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrate plus nitrate, dissolved (mg/L as N)	Boron, dissolved (µg/L)	Organic carbon, total (mg/L as C)
Streamflow--Continued										
Beals Creek site:										
Elbow Creek	08-26-87	2,100	5.0	5.3	--	7.9	5,210	--	2,000	20
Elm Creek site:										
Coyote Creek	08-27-87	520	1.1	2.2	--	14	1,880	--	520	5.4
Shallow aquifer: Valley alluvial--Ogallala Formation subcrop probable										
28-44-101	08-26-87	880	4.0	2.3	--	20	3,920	--	4,200	25
	03-06-89	1,000	--	.41	0.008	--	--	<0.10	--	--
28-52-103	08-26-87	22	4.0	.17	--	55	2,530	--	440	3.4
	03-06-89	68	--	.55	.040	--	--	12	--	--
28-52-504	08-26-87	950	10	14	--	41	2,890	--	2,000	4.5
	03-06-89	1,000	--	5.7	.071	--	--	32	--	--
28-52-702	08-26-87	1,900	4.0	14	--	25	5,490	--	2,900	40
	03-06-89	3,000	--	21	.550	--	--	.45	--	--
Shallow aquifer: Valley alluvial--Dockum Group subcrop probable										
28-32-208	08-27-87	570	.20	3.8	--	18	4,810	--	230	1.3
	03-06-89	510	--	2.8	.028	--	--	<.100	--	--
28-32-503	08-28-87	190	<.10	1.6	--	7.1	3,800	--	200	4.2
28-32-603	08-27-87	91	.10	.60	--	22	3,310	--	210	<.10
	03-06-89	95	--	4.7	5.9	--	--	--	--	--
Shallow aquifer: Valley alluvial--Guadalupe Series subcrop probable										
29-59-701	08-31-87	81	.60	.22	--	26	1,550	--	470	11
	02-01-89	200	--	.29	.032	--	--	1.8	--	--
Shallow aquifer: Valley alluvial--Clear Fork Group subcrop probable										
42-02-102	08-26-87	410	.60	2.2	--	17	2,420	--	370	1.0
Shallow aquifer: Dockum										
28-24-503	08-27-87	560	4.0	.71	--	9.9	1,820	--	1,800	.40
	03-07-89	600	--	.71	.110	--	--	.96	--	--
28-24-704	08-27-87	1,400	1.9	2.3	--	8.1	3,260	--	1,700	.20
28-24-805	08-27-87	690	2.7	.18	--	25	2,540	--	1,200	2.7
	03-07-89	540	--	2.3	.140	--	--	43	--	--

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iodide, dissolved (mg/L)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrate plus nitrate, dissolved (mg/L as N)	Boron, dissolved (µg/L)	Organic carbon, total (mg/L as C)
Shallow aquifer: Dockum--Continued										
28-32-906	08-27-87	510	0.10	1.5	--	21	3,520	--	100	2.8
	03-06-89	1,300	--	3.0	0.003	--	--	<0.10	–	--
28-40-312	08-25-87	150	.50	2.7	--	17	3,830	--	240	.50
	03-07-89	150	--	.36	.008	--	--	.81	–	--
28-40-602	08-25-87	460	.90	2.0	--	13	3,090	--	310	6.6
	03-07-89	460	--	2.2	.074	--	--	9.5	–	--
28-45-301	08-27-87	740	.80	14	--	16	2,220	--	1,500	.40
	03-06-89	750	--	3.4	.260	--	--	.49	–	--
28-48-901	08-25-87	1,000	4.0	4.8	--	13	4,230	--	2,600	4.5
	03-07-89	920	--	5.2	.510	--	--	73	–	--
28-54-304	08-26-87	370	2.5	3.5	--	40	1,300	--	520	3.4
	03-07-89	820	--	3.2	.150	--	--	8.0	–	--
28-54-305	03-07-89	3,600	--	9.0	.640	--	--	4.7	–	--
28-55-101	08-26-87	5,600	1.0	23	--	58	9,930	--	970	28
	03-07-89	5,500	--	27	.150	--	--	.94	–	--
29-17-505	08-27-87	910	6.0	.74	--	22	3,220	--	2,200	4.9
29-25-707	08-28-87	2,000	.30	13	--	21	3,780	--	240	20
29-26-401	08-28-87	350	1.1	3.1	--	20	2,610	--	410	4.0
29-33-202	08-25-87	760	<.10	2.4	--	<1	1,640	--	100	16
29-33-206	03-06-89	32	--	.25	.003	--	--	2.7	–	--
29-41-705	08-25-87	2,700	1.7	14	--	18	10,900	--	1,600	8.3
	03-07-89	770	--	3.5	.085	--	--	25	–	--
Shallow aquifer: Whitehorse-San Andres										
29-50-603	08-25-87	980	1.1	2.3	--	18	3,900	--	550	3.2
	03-06-89	650	--	3.5	.023	--	--	--	–	--
29-51-701	08-25-87	340	.70	.60	--	4.0	6,480	--	8,100	3.0
	03-06-89	260	--	.38	.037	--	--	.10	–	--
29-58-611	08-31-87	1,600	.80	2.8	--	42	5,040	--	450	2.5
	02-01-89	1,600	--	2.9	.035	--	--	3.4	–	--
29-59-505	08-31-87	800	.50	8.0	--	4.4	2,180	--	340	5.6
	02-01-89	1,000	--	3.3	.081	--	--	.20	–	--

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iodide, dissolved (mg/L)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrate plus nitrate, dissolved (mg/L as N)	Boron, dissolved (µg/L)	Organic carbon, total (mg/L as C)
Shallow aquifer: Whitehorse-San Andres--Continued										
29-60-803	08-31-87	130	1.4	0.90	--	20	2,460	--	210	0.6
	02-01-89	340	--	1.7	0.017	--	--	0.25	-	--
43-03-904	08-31-87	290	1.0	1.4	--	18	3,470	--	560	1.4
	02-01-89	270	--	1.2	.029	--	--	.34	-	--
43-05-302	09-02-87	290	1.0	1.7	--	13	2,520	--	960	7.3
	01-31-89	140	--	.77	.023	--	--	.67	-	--
Shallow aquifer: San Angelo										
43-05-502	09-01-87	440	1.1	1.5	--	12	7,130	--	5,800	2.6
	02-01-89	500	--	1.1	.092	--	--	8.7	-	--
43-06-301	09-02-87	1,400	.20	7.3	--	19	3,480	--	610	19
	01-31-89	1,300	--	6.6	.036	--	--	57	-	--
43-13-304	09-01-87	740	.20	3.8	--	5.4	5,270	--	1,100	16
	01-31-89	700	--	2.7	.035	--	--	.71	-	--
43-13-602	01-31-89	1,600	--	3.6	.170	--	--	3.7	-	--
43-13-603	09-01-87	1,400	1.5	3.1	--	7.9	3,340	--	1,400	4.2
	01-31-89	1,400	--	2.4	.100	--	--	.24	-	--
43-14-102-spring	09-01-87	3,500	1.1	13	--	20	9,140	--	2,600	7.1
	01-31-89	4,500	--	14	.150	--	--	<.10	-	--
43-14-609	02-23-89	290	--	1.3	.051	--	--	1.3	-	--
43-37-704	08-26-87	1,600	.50	4.6	--	40	4,250	--	910	2.4
Shallow aquifer: Clear Fork										
42-02-701	08-26-87	1,100	3.2	4.9	--	19	2,830	--	800	3.3
42-09-501	09-04-87	1,400	1.0	5.6	--	17	4,000	--	630	5.3
43-06-802	09-02-87	440	.20	2.3	--	5.1	4,340	--	880	.80
	01-31-89	410	--	2.1	.047	--	--	<.10	-	--
43-24-501	09-02-87	640	1.3	1.9	--	18	2,700	--	630	.80
43-24-802	08-26-87	2,200	1.6	7.9	--	21	5,430	--	1,100	5.6
43-40-601	08-25-87	1,700	1.2	11	--	19	5,970	--	2,100	4.0

Table 1. Water-quality data for streamflow, shallow aquifers, and deep aquifers in the upper Colorado River Basin, Texas, 1987 and 1989--Continued

Streamflow-study site, well, or spring (shown on plate 1)	Date of sample	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iodide, dissolved (mg/L)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrate plus nitrate, dissolved (mg/L as N)	Boron, dissolved (μg/L)	Organic carbon, total (mg/L as C)
Deep aquifer: Wolfcamp--Permian System										
Coleman Junction Limestone oil well	08-26-87	(20,000)[1]	0.60	45	--	1.8	--	--	9,000	1.5
Deep aquifer: Strawn--Pennsylvanian System										
SSR oil well	08-27-87	(37,000)[1]	<.10	90	--	2.4	--	--	3,200	50
Veribest oil well	08-27-87	59,000	--	330	--	--	105,000	--	6,300	35

[1] Chloride concentrations in parentheses were estimated according to the following method:
chloride = (calcium + magnesium + sodium + potassium) - (sulfate + alkalinity, as bicarbonate), where all data are in equivalent charge per liter.

Table 3. Salt-norm classifications of streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas

[--, normative mineral not present]

Streamflow-study site, well, or spring[1] (shown on plate 1)	Salt-norm classification[2]	Normative salts, anhydrous weight percentage[3]					
		Halite	Antarcticite and tachyhydrite	Bischofite and carnallite	Anhy-drite	Alkali or magnesium sulfate salts	Carbonate and nitrate salts
Streamflow							
Colorado River sites:							
Bull Creek	Brine-mixed	58.3	9.3	3.0	19.7	--	9.6
Bluff Creek	Brine	45.8	--	5.8	39.3	2.9	6.1
Colorado River	Brine	76.5	--	--	11.8	9.8	1.8
Canyon Creek	Meteoric-SO_4	42.1	--	.8	35.7	13.4	7.8
Little Sulphur Creek	Meteoric-SO_4	26.1	--	--	--	59.2	11.9
Bone Hollow Creek	Meteoric-SO_4	26.2	--	--	24.6	35.8	13.1
Jayhawk Creek	Meteoric-SO_4	32.3	--	--	31.3	33.9	2.3
Beals Creek site:							
Elbow Creek	Brine	58.8	--	6.6	18.3	12.6	3.3
Elm Creek site:							
Coyote Creek	Meteoric-SO_4	39.2	--	5.2	35.5	10.9	9.0
Shallow aquifer: Valley alluvial--Ogallala Formation subcrop probable							
28-44-101	Meteoric-SO_4	36.4	--	--	--	46.7	14.5
28-52-103	Gypsum	1.4	--	--	76.1	18.9	3.2
28-52-504	Brine	50.1	--	4.5	18.2	18.4	7.9
28-52-702	Brine	52.9	--	3.5	9.0	31.8	2.4
Shallow aquifer: Valley alluvial--Dockum Group subcrop probable							
28-32-208	Gypsum	11.4	--	6.8	49.3	23.8	8.7
28-32-503	Meteoric-SO_4	8.3	--	--	35.0	55.5	1.3
28-32-603	Meteoric-SO_4	4.5	--	--	--	86.6	8.4
Shallow aquifer: Valley alluvial--Guadalupe Series subcrop probable							
29-59-701	Meteoric-SO_4	8.6	--	--	32.2	52.9	6.2
Shallow aquifer: Valley alluvial--Clear Fork Group subcrop probable							
6	Brine-mixed	44.7	36.5	.1	16.0	--	2.2
42-02-102	Gypsum	24.8	--	2.7	50.3	12.2	9.9

Footnotes at end of table.

Table 3. Salt-norm classifications of streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Salt-norm classification[2]	Normative salts, anhydrous weight percentage[3]					
		Halite	Antarcticite and tachyhydrite	Bischofite and carnallite	Anhydrite	Alkali or magnesium sulfate salts	Carbonate and nitrate salts
Shallow aquifer: Leona--Clear Fork Group subcrop probable							
28	Gypsum	16.4	--	13.4	55.2	--	13.3
Shallow aquifer: wells open to both Leona and Clear Fork aquifers							
25	Brine-mixed	34.1	33.2	.3	11.0	--	21.0
27	Meteoric-CO_3	26.0	9.7	1.5	22.1	--	40.3
38	Brine-mixed	33.7	32.5	.9	13.4	--	19.0
42	Brine-mixed	41.4	34.5	2.3	13.2	--	8.1
53b	Brine-mixed	45.6	30.6	.5	13.8	--	9.2
Shallow aquifer: Dockum							
98	Meteoric-SO_4	47.3	--	--	--	48.5	3.8
99	Brine	54.2	--	--	--	39.8	5.3
28-24-503	Brine	49.0	--	--	--	28.6	21.1
28-24-704	Brine	70.7	--	--	--	24.4	4.1
28-24-805	Brine	45.4	--	--	--	41.5	12.4
28-32-906	Gypsum	23.7	--	--	51.8	19.0	5.5
28-40-312	Meteoric-SO_4	6.5	--	--	30.3	57.8	5.4
28-40-602	Meteoric-SO_4	24.4	--	--	23.0	45.4	7.2
28-45-301	Brine	55.9	--	--	18.4	21.6	3.7
28-48-901	Meteoric-SO_4	39.7	--	--	--	50.6	9.0
28-54-304	Brine	46.9	--	3.4	32.8	--	16.3
28-55-101	Brine-mixed	41.5	45.8	1.4	10.6	--	.6
29-17-505	Meteoric-SO_4	46.5	--	--	22.5	25.0	5.5
29-25-707	Brine-mixed	36.4	44.7	.9	13.0	--	5.0
29-26-401	Gypsum	22.3	--	--	39.1	31.2	7.3
29-33-202	Brine-mixed	25.9	41.1	3.6	24.5	--	4.8
29-41-705	Meteoric-SO_4	40.6	--	--	14.6	42.3	2.4
Shallow aquifer: Whitehorse-San Andres							
29-50-603	Gypsum	18.1	--	18.5	54.0	5.8	3.5

Footnotes at end of table.

Table 3. Salt-norm classifications of streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Salt-norm classification[2]	Normative salts, anhydrous weight percentage[3]					
		Halite	Antarcticite and tachyhydrite	Bischofite and carnallite	Anhy-drite	Alkali or magnesium sulfate salts	Carbonate and nitrate salts
Shallow aquifer: Whitehorse-San Andres--Continued							
29-51-701	Meteoric-SO_4	8.3	--	--	--	90.1	0.5
29-58-611	Gypsum	31.1	15.5	2.0	49.7	--	1.6
29-59-505	Brine	58.7	--	.5	17.0	18.9	4.8
29-60-803	Gypsum	7.0	--	1.6	73.4	13.0	4.8
43-03-904	Gypsum	13.9	--	--	60.5	19.6	5.9
43-05-302	Meteoric-SO_4	19.0	--	--	26.6	48.8	5.4
Shallow aquifer: San Angelo							
34	Meteoric-CO_3	25.3	12.7	1.1	11.3	--	48.4
35	Brine-mixed	60.8	16.7	.9	8.9	--	12.4
37	Brine-mixed	18.0	30.4	6.2	37.0	--	7.8
60a	Brine	58.8	--	4.9	16.3	16.6	3.1
60b	Brine	83.7	3.1	3.6	8.8	--	.6
61	Brine-mixed	71.8	13.5	2.7	8.7	--	2.8
43-05-502	Meteoric-SO_4	10.0	--	--	--	84.7	3.2
43-06-301	HS-mixed	43.3	--	20.5	27.5	6.7	2.0
43-13-304	Gypsum	23.4	--	--	39.0	36.3	1.2
43-13-603	Brine	69.4	--	--	8.3	15.9	6.2
43-14-102-spring	Brine	57.9	--	5.0	23.5	9.6	3.9
43-37-704	Brine-mixed	49.4	8.6	3.2	30.2	--	8.6
Shallow aquifer: Clear Fork							
3	Meteoric-CO_3	31.8	--	--	17.7	--	50.2
4	Brine-mixed	62.4	8.3	11.4	12.2	--	3.7
5	Gypsum	28.6	--	2.7	47.5	7.6	12.6
8	Gypsum	16.0	--	8.4	62.7	4.8	7.1
10-spring	HS-mixed	31.2	2.2	14.1	36.9	--	14.6
11-spring	HS-mixed	31.1	--	17.4	35.3	--	14.5

Footnotes at end of table.

Table 3. Salt-norm classifications of streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Salt-norm classification[2]	Normative salts, anhydrous weight percentage[3]					
		Halite	Antarcticite and tachyhydrite	Bischofite and carnallite	Anhydrite	Alkali or magnesium sulfate salts	Carbonate and nitrate salts
		Shallow aquifer: Clear Fork--Continued					
12-spring	HS-mixed	31.5	--	17.7	33.3	--	15.7
13	Gypsum	30.7	--	9.5	33.1	18.6	7.1
14-spring	Brine	37.7	--	10.4	23.7	--	26.6
17	Brine-mixed	33.8	28.0	.6	17.2	--	20.0
24	Brine-mixed	24.8	28.4	.9	18.5	--	27.0
26	Brine-mixed	27.3	22.1	.8	27.1	--	22.1
40	Brine-mixed	31.8	29.5	.8	26.2	--	10.4
41	Brine-mixed	38.3	25.9	.8	19.3	--	15.1
43	Gypsum	21.9	--	3.0	52.9	14.3	7.3
42-02-701	Brine	51.2	--	10.6	22.0	6.2	9.7
42-09-501	HS-mixed	28.8	--	23.9	38.5	.6	8.1
43-06-802	Meteoric-SO_4	16.8	--	--	28.9	49.1	5.1
43-24-501	Meteoric-SO_4	36.7	--	2.8	31.9	19.3	9.1
43-24-802	Brine-mixed	30.7	32.6	.4	32.1	--	4.1
43-40-601	Gypsum	34.5	--	10.9	46.1	5.4	2.9
		Shallow aquifer: Unknown--Clear Fork aquifer probable					
15-spring	Gypsum	27.9	--	--	43.1	23.9	4.4
16	Brine	38.4	--	3.2	26.5	--	30.2
36	Brine-mixed	47.5	33.9	1.1	13.1	--	3.9
39	Brine-mixed	32.2	46.0	.6	10.6	--	10.1

[1] Data for wells and springs with one- and two-digit numbers are from Richter and Kreitler (1985), Dutton and Simpkins (1986), and Richter and others (1990).

[2] Salt-norm classifications of the cause of salinity in water (Bodine and Jones, 1986): Meteoric norms derive solutes from weathering and dissolution of carbonate (Meteoric-CO_3) and sulfate (Meteoric-SO_4) minerals. Meteoric-CO_3 norms are dominated by carbonate normative minerals. Meteoric-SO_4 norms are dominated by sodium, magnesium, and potassium sulfate normative minerals. Marine norms classed in this study include water that derives salinity from dissolution of anhydrite or gypsum (gypsum), halite (brine), or by evaporative concentration or by mixing with deep-aquifer brines (HS-mixed). Gypsum and brine norms are dominated by normative anhydrite and normative halite salts, respectively. HS-mixed norms contain more than 12 percent of the sum of normative bischofite and carnallite salts. Diagenetic norms (brine-mixed) include more than 5 percent of the sum of normative antarcticite and normative tachyhydrite. A brine-mixed norm is characteristic of deep-aquifer brines with the cation composition modified by reactions with shallow-aquifer minerals.

[3] Anhydrous weight percentages for an analysis may not total 100 because of trace normative salts.

Table 4. Trace-species/chloride ratios and classifications of the principal sources of chloride in streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas

[Oil- and gas-field boundaries are taken from (1) plate 6 and (2) Midland Map Co., 1986 (Coke, Concho, Howard, Mitchell, Scurry, and Tom Green Counties) and Heydrick Map Services, 1986 (Runnels County). mg/L, milligrams per liter; --, no data; >, greater than]

Streamflow-study site, well, or spring[1] (shown on plate 1)	Year sampled	Chloride (mg/L)	Bromide x 10^4/ chloride weight ratio	Chloride/ nitrate equivalent ratio	Source of chloride[2]	Name of oil and gas field within 1 mile of sampled site (producing system[3])
			Streamflow			
Colorado River sites:						
Bull Creek	1987	340	147	--	U	Sharon Ridge (Pr)
Bluff Creek	1987	870	36	--	Pr,Pn	Sharon Ridge (Pr)
Colorado River	1987	2,900	5.2	--	H	--
Canyon Creek	1987	450	38	--	U	Sharon Ridge (Pr,Pn)
Little Sulphur Creek	1987	120	40	--	U	--
Bone Hollow Creek	1987	310	142	--	U	--
Jayhawk Creek	1987	920	54	--	Pn	Champion Lake (Pr)
Beals Creek site:						
Elbow Creek	1987	2,100	25	--	Pr	Moore (Pr,Pn,O)
Elm Creek site:						
Coyote Creek	1987	520	42	--	U	Ballinger (Pn)
			Shallow aquifer: Valley alluvial--Ogallala Formation subcrop probable			
28-44-101	1987	880	26	--	Pr,H	Varel (Pr)
	1989	1,000	4.1	>3,950	H	
28-52-103	1987	22	77	--	U	Moore (Pr,Pn,O)
	1989	68	81	2.2	Shal.	
28-52-504	1987	950	147	--	U	Moore (Pr,Pn,O)
	1989	1,000	57	12	Pn	
28-52-702	1987	1,900	74	--	Pn	Lomax-
	1989	3,000	70	2,630	Pn	Wilkerson (Pn)
			Shallow aquifer: Valley alluvial--Dockum Group subcrop probable			
28-32-208	1987	570	67	--	Pr,Pn	Sharon Ridge (Pr)
	1989	510	55	>2,010	Pr,Pn	
28-32-503	1987	190	84	--	U	Sharon Ridge (Pr)
28-32-603	1987	91	66	--	U	Sharon Ridge
	1989	95	495	1.9	Shal.	(Pr,Pn)

Footnotes at end of table.

Table 4. Trace-species/chloride ratios and classifications of the principal sources of chloride in streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Year sampled	Chloride (mg/L)	Bromide x 10^4/ chloride weight ratio	Chloride/ nitrate equivalent ratio	Source of chloride[2]	Name of oil and gas field within 1 mile of sampled site (producing system[3])
Shallow aquifer: Valley alluvial--Guadalupe Series subcrop probable						
29-59-701	1987	81	27	--	U	Jameson (Pr,Pn)
	1989	200	15	44	H	
Shallow aquifer: Valley alluvial--Clear Fork Group subcrop probable						
6	1985	5,130	7.4	8,970	H	--
42-02-102	1987	410	54	--	U	Rivers (Pn)
Shallow aquifer: Leona--Clear Fork Group subcrop probable						
28	1985	516	3.9	6.1	Shal.	Veribest, N (Pn)
Shallow aquifer Wells open to both Leona and Clear Fork aquifers						
25	1985	980	34	7.5	Shal.	Veribest, E (Pn)
27	1985	236	42	4.2	Shal.	--
38	1985	735	37	10	Shal.	--
42	1987	1,880	33	39	Pn	Floyd Miller (Pn)
53b	1987	1,780	37	50	Pn	--
Shallow aquifer: Dockum						
98	1985	1,571	27	--	Pr	Vealmoor (Pr,Pn)
99	1985	1,183	35	--	Pr,Pn	--
28-24-503	1987	560	13	--	H	Diamond-M (Pr,Pn) and Sharon Ridge (Pr)
	1989	600	12	247	H	
28-24-704	1987	1,400	16	--	Pr,H	Sharon Ridge (Pr)
28-24-805	1987	690	2.6	--	H	Sharon Ridge (Pr)
	1989	540	43	5	Shal.	
28-32-906	1987	510	29	--	U	Sharon Ridge (Pr)
	1989	1,300	23	>5,140	Pr,H	
28-40-312	1987	150	180	--	U	Sharon Ridge (Pr)
	1989	150	24	73	U	
28-40-602	1987	460	44	--	U	--
	1989	460	48	19	U	
28-45-301	1987	740	189	--	U	--
	1989	750	45	605	Pr,Pn	

Footnotes at end of table.

Table 4. Trace-species/chloride ratios and classifications of the principal sources of chloride in streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Year sampled	Chloride (mg/L)	Bromide x 10^4/ chloride weight ratio	Chloride/ nitrate equivalent ratio	Source of chloride[2]	Name of oil and gas field within 1 mile of sampled site (producing system[3])
			Shallow aquifer: Dockum--Continued			
28-48-901	1987	1,000	48	--	Pn	--
	1989	920	57	5	Shal.	
28-54-304	1987	370	95	--	U	Snyder (Pr,Pn)
	1989	820	39	41	Pr,Pn	
28-54-305	1989	3,600	25	303	Pr	Snyder (Pr,Pn)
28-55-101	1987	5,600	41	--	Pn	Snyder (Pr,Pn)
	1989	5,500	49	2,310	Pn	
29-17-505	1987	910	8.1	--	H	Kelly-Snyder (Pr,Pn)
29-25-707	1987	2,000	65	--	Pn	Kelly-Snyder (Pr,Pn)
29-26-401	1987	350	89	--	U	--
29-33-202	1987	760	32	--	U	--
29-33-206	1989	32	78	4.7	Shal.	Sharon Ridge (Pr)
29-41-705	1987	2,700	52	--	Pn	--
	1989	770	46	12	Pr,Pn	
			Shallow aquifer: Whitehorse-San Andres			
29-50-603	1987	980	24	--	Pr	--
	1989	650	54	12	Pr,Pn	
29-51-701	1987	340	18	--	U	Jameson, N (Pn,O)
	1989	260	15	1,030	U	
29-58-611	1987	1,600	18	--	Pr,H	Jameson (Pr,Pn)
	1989	1,600	18	186	Pr,H	
29-59-505	1987	800	100	--	U	Jameson, N (Pn,O)
	1989	1,000	33	1,980	Pr,Pn	
29-60-803	1987	130	69	--	U	I.A.B. (Pr,Pn)
	1989	340	50	540	U	
43-03-904	1987	290	48	--	U	Green Mtn. (Pn)
	1989	270	44	314	U	
43-05-302	1987	290	59	--	U	--
	1989	140	55	83	U	
			Shallow aquifer: San Angelo			
34	1987	200	95	15	U	--

Footnotes at end of table.

Table 4. Trace-species/chloride ratios and classifications of the principal sources of chloride in streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Year sampled	Chloride (mg/L)	Bromide x 10^4/ chloride weight ratio	Chloride/ nitrate equivalent ratio	Source of chloride[2]	Name of oil and gas field within 1 mile of sampled site (producing system[3])
			Shallow aquifer: San Angelo--Continued			
35	1987	1,425	33	42	Pr,Pn	--
37	1985	1,060	43	40	Pr,Pn	--
60a	1987	6,430	22	>5,600	Pr	Nasworthy (Pn)
60b	1987	33,140	18	>29,000	Pr	Nasworthy (Pn)
61	1987	5,280	16	385	Pr	--
43-05-502	1987	440	34	--	U	J.L.H. (O)
	1989	500	22	23	Pr,H	
43-06-301	1987	1,400	52	--	Pn	Ft. Chadbourne (Pn)
	1989	1,300	51	9	Shal.	
43-13-304	1987	740	51	--	Pr,Pn	Wendkirk, W and
	1989	700	39	390	U	Capps (Pn)
43-13-602	1989	1,600	23	171	Pr	--
43-13-603	1987	1,400	22	--	Pr	Wendland (Pn)
	1989	1,400	17	2,300	Pr,H	
43-14-102-spring	1987	3,500	37	--	Pn	Wendkirk (Pn)
	1989	4,500	31	>17,800	Pn	
43-14-609	1989	290	45	88	U	Bronte, SE (Pn)
43-37-704	1987	1,600	29	--	Pr	--
			Shallow aquifer: Clear Fork			
3	1985	166	54	1.9	Shal.	Norton, E. (Pn)
4	1985	2,330	24	>4,070	Pr	Byers (Pn)
5	1985	452	40	158	U	Ballinger (Pn)
8	1985	595	40	33	U	--
10-spring	1985	699	36	8.2	Shal.	--
11-spring	1985	723	35	9.9	Shal.	--
12-spring	1985	685	35	7.6	Shal.	--
13	1985	983	33	30	Pr,Pn	--
14-spring	1985	454	35	4.7	Shal.	--

Footnotes at end of table.

Table 4. Trace-species/chloride ratios and classifications of the principal sources of chloride in streamflow and shallow-aquifer water in the upper Colorado River Basin, Texas--Continued

Streamflow-study site, well, or spring[1] (shown on plate 1)	Year sampled	Chloride (mg/L)	Bromide x 10^4/ chloride weight ratio	Chloride/ nitrate equivalent ratio	Source of chloride[2]	Name of oil and gas field within 1 mile of sampled site (producing system[3])
Shallow aquifer: Clear Fork--Continued						
17	1985	720	35	7.6	Shal.	--
24	1985	454	44	6.9	Shal.	--
26	1985	461	41	7	Shal.	Veribest, E. (Pn)
40	1987	1,060	45	26	Pn	Floyd Miller (Pn,O)
41	1987	920	42	12	Pr,Pn	Floyd Miller (Pn,O)
43	1985	639	24	>1,120	Pr,H	--
	1987	4,450	15	3,890	Pr	
42-02-701	1987	1,100	45	--	Pn	Freeman (O) and Nora (Pn)
42-09-501	1987	1,400	40	--	Pn	Ballinger (Pn)
43-06-802	1987	440	52	--	U	Bronte (Pn,O)
	1989	410	51	>1,620	U	
43-24-501	1987	640	30	--	Pr,H	--
43-24-802	1987	2,200	36	--	Pn	Rowena (Pn)
43-40-601	1987	1,700	65	--	Pn	--
Shallow aquifer: Unknown--Clear Fork aquifer probable						
15-spring	1985	735	42	>1,290	Pr,Pn	--
16	1985	343	47	5	Shal.	--
36	1985	2,650	23	113	Pr	--
39	1985	1,310	34	26	Pr,Pn	--

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[1] Data for wells and springs with one- and two-digit numbers are from Richter and Kreitler (1985), Dutton and Simpkins (1986), and Richter and others (1990).

[2] Source of chloride: Water chemistries were classified according to their similarity to an ideal mixture between water with small chloride concentrations and:

U - an unknown source of chloride
Pn - water from Pennsylvanian System deep aquifers
Pr - water from Permian System deep aquifers
H - halite dissolution brine
Pn,Pr - water from Pennsylvanian System deep aquifers and Permian System deep aquifers
Pr,H - water from Permian System deep aquifers and halite dissolution brine
Shal. - water from dissolution of chloride bearing minerals from the unsaturated zone

[3] Producing system: Geologic system from which oil or gas production or both is documented for an oil and gas field.

Pr - Permian System
Pn - Pennsylvanian System
O - Ordovician System

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