TEXAS
WATER
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BOARD

Report 210

GROUND-WATER RESOURCES OF THE CARRIZO AQUIFER IN THE WINTER GARDEN AREA OF TEXAS

VOLUME 1

September 1976

TEXAS WATER DEVELOPMENT BOARD

REPORT 210

GROUND-WATER RESOURCES OF THE CARRIZO AQUIFER IN THE WINTER GARDEN AREA OF TEXAS

VOLUME I

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September 1976

TEXAS WATER DEVELOPMENT BOARD

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Published and distributed
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Texas Water Development Board
Post Office Box 13087
Austin, Texas 78711

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GROUND-WATER RESOURCES OF THE CARRIZO AQUIFER IN THE WINTER GARDEN AREA OF TEXAS

ABSTRACT

The Winter Garden Area of Texas lies southwest of the San Marccos River and within the Guadalupe, San Antonio, Nueces, and Rio Grande basins. It consists of all or parts of Atascosa, Bexar, Caldwell, Dimmit, Frio, Gonzales, Guadalupe, Karnes, La Salle, Live Oak, McMullen, Maverick, Medina, Uvalde, Webb, Wilson, and Zavala Countie:;. Within the Winter Garden Area is found the Winter Garden District which includes Dimmit and Zavala Counties; and eastern Maverick County.

The Carrizo aquifer is the most continuous, permeable, and most developed (heavily pumped) water-bearing unit in the Winter Garden Area. Throughout most of the Winter Garden Area, the Carrizo aquifer yields ground water which is acceptable for most irrigation, public supply, and industrial purposes.

Recharge to the Carrizo aquifer enters by infiltration from rainfall and from streams which flow across the outcrop. The average rate of recharge to the Carrizo aquifer in the Winter Garden Area is about 100,000 acre-feet per year or 89 mgd (million gallons per day). In addition, leakage to the aquifer from other formations occurs in Dimmit, Frio, and Zavala Counties; an estimated 9,500 acre-feet per year (8.5 mgd) leaked into the Carrizo through confining beds and down uncemented well bores during the period 1963-1969. Average annual pumpage for the period 1963-1969 was approximately 272,000 acre-feet (243 mgd). Thus, for this period about 162,500 acre-feet per year (145 mgd) was removed annually from storage. These large annual withdrawals of ground water from storage have caused declines in Carrizo aquifer water levels, which directly affect the cost of pumping water and are also related to water-quality changes within the aquifer, particularly in the Winter Garden District (Dimmit, Zavala, and eastern Maverick Counties).

One of the primary objectives of this study was to simulate the Carrizo aquifer in the Winter Garden Area with a digital computer mathematical model. The simulations for the period 1970 through 2020 indicate the following: (a) in the heavily irrigated areas near Batesville and east of Carrizo Springs and Crystal City in Dimmit and Zavala Counties, water levels will continue to decline rapidly; (b) elsewhere in the Winter Garden Area, water levels will slowly decline if pumpage remains unregulated and occurs at predicted rates; (c) a firm water supply of 20,000 to 40,000 acre-feet per year (18 to 36 mgd) of ground water from wells can be developed in Wilson County for municipal use in the San Antonio region; (d) approximately 330,000 acre-feet per year (294 mgd) of ground water can be developed annually from the Carrizo aquifer and not lower water levels below a 400-foot level below land surface or below the top of the water-bearing sands until the year 2020, representing an increase of 58,000 acre-feet per year (52 mgd) over the withdrawals of 1963-l 969; and (e) the areas most favorable for development of additional ground-water supplies are in Wilson and Gonzales Counties.

GROUND-WATER RESOURCES OF THE CARRIZO AQUIFER IN THE WINTER GARDEN AREA OF TEXAS

INTRODUCTION

Purpose and Scope

Field study was begun in October 1967 to determine the ground-water resources of the Winter Garden Area of Texas with emphasis on the Carrizo aquifer. The primary objectives of this study were: (a) to determine the regional geohydrologic characteristics of the Carrizo aquifer; (b) to establish monitoring programs for pumpage, water levels, and water quality with respect to the Carrizo aquifer for continuous evaluation of ground-water availability and dependability on a regional basis; (c) to examine the feasibility of artificially recharging the Carrizo aquifer; and (d) to use a digital computer model of the Carrizo aquifer to evaluate the aquifer's response to pumping and the probable future ground-water conditions. Field work for this study was completed in the spring of 1970.

Volume I summarizes the results of this investigation, and contains information on the amounts of water that have been and can be produced from the Carrizo aquifer, its hydrologic characteristics, and the chemical quality of its water. The water-bearing strata of the Wilcox Group and other aquifers of the Claiborne Group are also discussed. Volume II contains supporting basic data: records of 3,214 water wells, records of water levels in 474 wells, and chemical analyses of water samples from 1,553 wells. Also available for reference in the files of the Texas Water Development Board are drillers' logs of 711 wells that were used in the study.

Location and Population

The area covered by this report, which will be referred to as the Winter Garden Area, is the area southwest of the San Marcos River in which the Carrizo aquifer contains fresh to slightly saline water. It consists of all or parts of Atascosa, Bexar, Dimmit, Frio, Gonzales, Guadalupe, Karnes, La Salle, Live Oak, McMullen, Maverick, Medina, Uvalde, Webb, Wilson, and Zavala Counties. Data were also collected east of the San Marcos River (Caldwell and eastern Guadalupe Counties), in order to minimize boundary effects of a computer simulation of the Carrizo aquifer. Although most of the maps in this report extend well east of the San Marcos River, all figures in the report concerning volume of ground water apply only to areas west of the San Marcos. The Winter Garden Area (west of the San Marcos River) consists of approximately 11,800 square miles and represents approximately 4.5 percent of the State's total area. Within the Winter Garden Area is the Winter Garden District, an irrigated region which produces vegetables in late winter and early spring in Dimmit, Zavala, and eastern Maverick Counties (Figure 1).

According to data in the 1970-71 Texas Almanac, the Winter Garden Area has a population of approximately 140,000, or about 1.2 percent of the State's population.

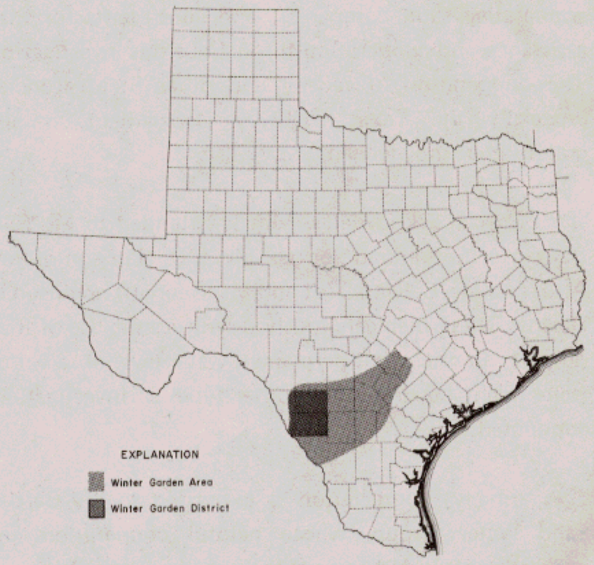


Figure 1.—Location and Extent of the Winter Garden Area and the Winter Garden District

Personnel

This report was prepared by the authors under the general direction of Lewis Seward, Principal Engineer-Project Development, and Robert Bluntzer, director, Water Availability Division. Tommy Barnes, geologist, assisted in assembling the data.

The digital computer mathematical model used to simulate the Carrizo aquifer was developed by George F. Pinder of the United States Geological Survey, and was modified by staff of the Board's Systems Engineering Division, under the direction of Lial Tischler and assisted by Al Austin, Tommy Knowles, and Allen White. Core drilling and the laboratory testing of drill cuttings and cores were done by staff of the Board's Materials Testing Laboratory and Core Drill Branch under the direction of James Sansom and Henry Sampson.

Acknowledgements

The authors appreciate the cooperation extended by the property owners in the Winter Garden Area who supplied information concerning their wells and, in many instances, also allowed access to their property and the use of their wells to monitor water-level changes and production capabilities. Acknowledgement is also extended to the water well drillers of the area, city officials, water superintendents, officials of independent water districts, electric and natural gas distribution cooperatives and companies, and consultants for their assistance and cooperation throughout this investigation. The cooperation of fede-al and other State agencies, especially the Texas Highway Department, is also gratefully acknowledged.

Special acknowledgement is extended to Mr. Billy Deagan of Sutherland Springs, Mr. J. D. Harrison of Palo Alto, and Mr. Calvin Hardt and Mr. George Thompson of Devine. These men generously permitted the use of their property in order that perrnanent water-level observation wells might be drilled and other types of investigations conducted.

Finally, appreciation is expressed to the Carrizo Sand Water Group, whose helpful cooperation and interest contributed toward the successful completion of this investigation and a better understanding of the ground-water resources of the Winter Garden Area.

WATER-BEARING STRATA OF THE WILCOX AND CLAIBORNE GROUPS

The Wilcox and Claiborne Groups contain the major aquifers within the study area. The strata of these units are marine and continental in origin and consist mainly of clay, cross-bedded river sand, beach sand, silt, and lignite. The stratigraphic units of the Wilcox and Claiborne, their approximate thickness, lithologic description, and water-bearing characteristics are given in Table 1. Their position in the subsurface is illustrated in the geohydrologic sections, Figures 27, 28, and 29. Estimates of the amount of ground water obtained from the aquifers for irrigation, public supply, and industrial purposes are given in Table 4.

For the purpose of this report, the Wilcox Group will be considered as an undifferentiated geologic unit. The upper section of the Wilcox contains some massive sand beds which are continental in origin. The middle portion is composed principally of nonmarine sand, clay, and lenticular beds of lignite. The basal portion contains mainly sand and clay of shallow marine origin. The Wilcox reaches a maximum thickness of about 2,800 feet and contains fresh to very saline water in the Winter Garden Area. Figure 2 illustrates the extent of sands containing fresh to slightly saline water-having less than 3,000 mg/l (milligrams per liter) dissolved solids--in the Wilcox aquifer (Wilcox Group). The approximate depth to and altitude of the top of the Wilcox aquifer are shown on Figure 10.

Overlying the Wilcox is the Carrizo Sand, the lowermost formation of the Claiborne Group. The Carrizo is composed mainly of very permeable, massive, cross-bedded, medium-grained sand and ranges in thickness from 150 to 1,200 feet in the report area. It is the principal and most developed (heavily pumped) water-bearing unit in the Winter Garden Area.

The general extent of fresh to slightly saline water in the Carrizo aquifer (Carrizo Sand) is given in Figure 2. The approximate depth to and altitude of the top of the Carrizo aquifer are illustrated in Figure 8. The total thickness and net sand thickness of the Carrizo aquifer are shown on Figure 9. The depth to and altitude of the base of the Carrizo aquifer are illustrated in Figure 10.

Because some of the sands in the Wilcox Group may be hydraulically connected with the Carrizo Sand,

Table 1.—Water-Bearing Characteristics of the Wilcox and Claiborne Groups in the Winter Garden Area

Yield, in gallons per minute	: small, less than 50; moderate, 50 to 500; large, over 500.
Salinity (total dissolved solids), in milligrams per liter:	fresh, less 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, over 35,000.

SYSTEM	SERIES	GROUP	GEOLOGIC UNIT		APPROXIMATE THICKNESS (FT)		CHARACTER OF ROCKS		WATER-BEARING PROPERTIES	
Tertiary	Eocene	Claiborne	Yegua Formation		700-1,000+		Clay, silt with interbedded thin lignites and sandstones. Some minor beds of limestone and oyster shells are found.		Yields small quantities of slightly to moderately saline water to wells in the outcrop area.	
			Laredo Formation	Cook Mountain Formation	600-700	400-500	Glauconitic sand and clay. Some gypsiferous clay and impure limestones.	Fossiliferous clay and shale. Some interbedded sandstone and limestone.	Yields small to moderate quantities of fresh to moderately saline water to wells.	Yields small quantities of slightly to moderately saline water to wells.
				Sparta Sand		40-200		Medium to fine sand. Some interbedded clay.		Yields small to moderate quantities of fresh to moderately saline water to wells.
			El Pico Clay	Weches Formation	700-1,500	50-200	Clay with interbedded sandstones, claystones, and lignite coal lenses.	Fossiliferous, glauconitic shale and sand.	Yields small quantities of slightly to moderately saline water to wells.	Not known to yield water to wells.
				Queen City Sand		500-1,400		Marine, medium to fine sand with interbedded clay and shale.		Yields small to moderate quantities of fresh to slightly saline water to wells.
			Bigford Formation	Reklaw Formation	200-900	200-400	Sands with interbedded silts and shales. Plant remains are abundant.	Clay with interbedded glauconitic sand.	Yields small to moderate quantities of fresh to very saline water to wells.	Yields small quantities of slightly to moderately saline water to wells in or near the outcrop.
			Carrizo Sand		150-1,200		Coarse to fine sand, massive, cross-bedded with a few partings of carbonaceous clay.		Principal aquifer in the report area. Yields moderate to large quantities of fresh to slightly saline water to wells.	
		Wilcox			0-2,800		Interbedded sand, clay, and silt with discontinuous beds of lignite. The shale and clay sometimes contain gypsum.		Yields small to moderate quantities of fresh to slightly saline water to wells in the northern and western parts of the report area.	

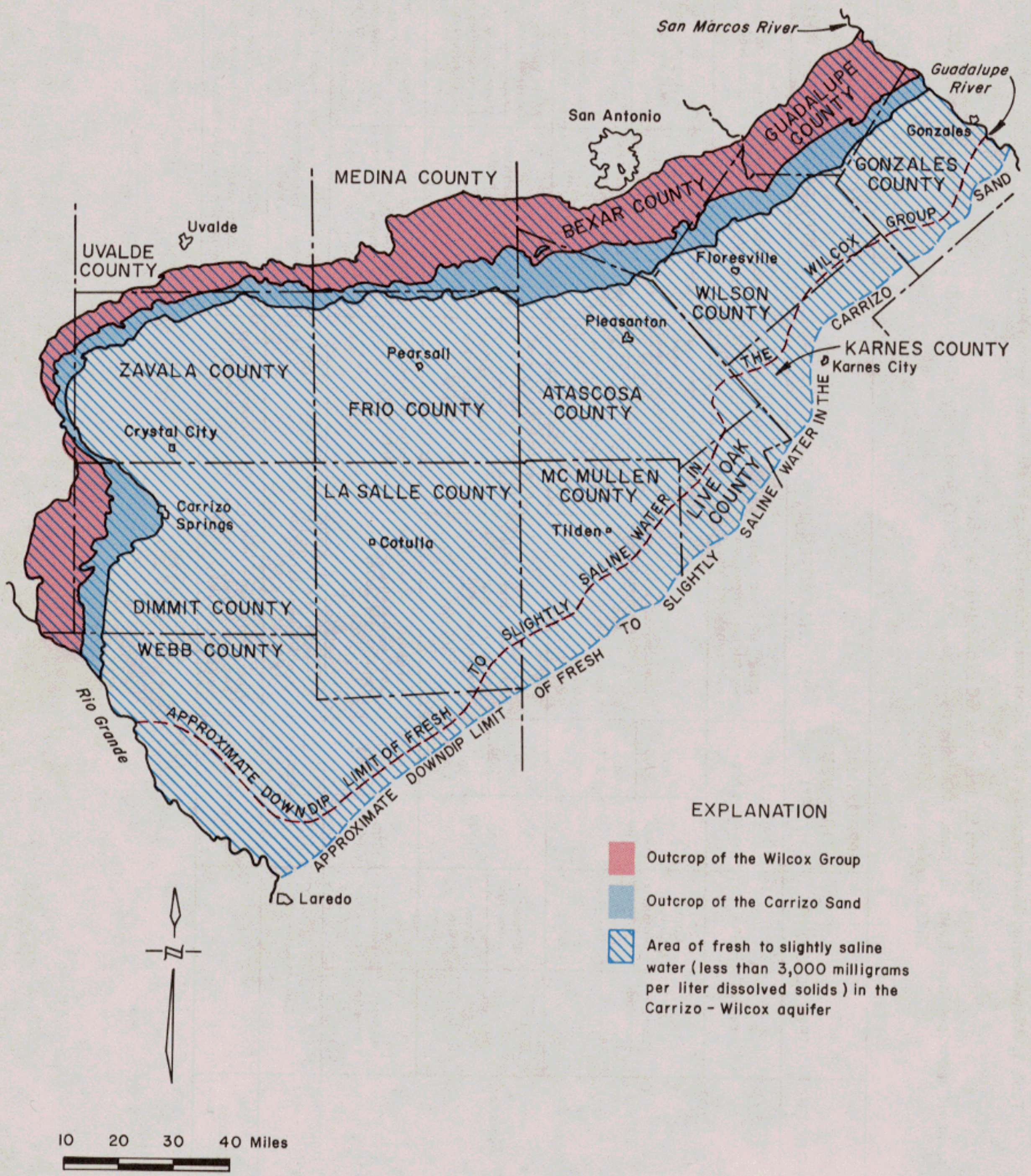
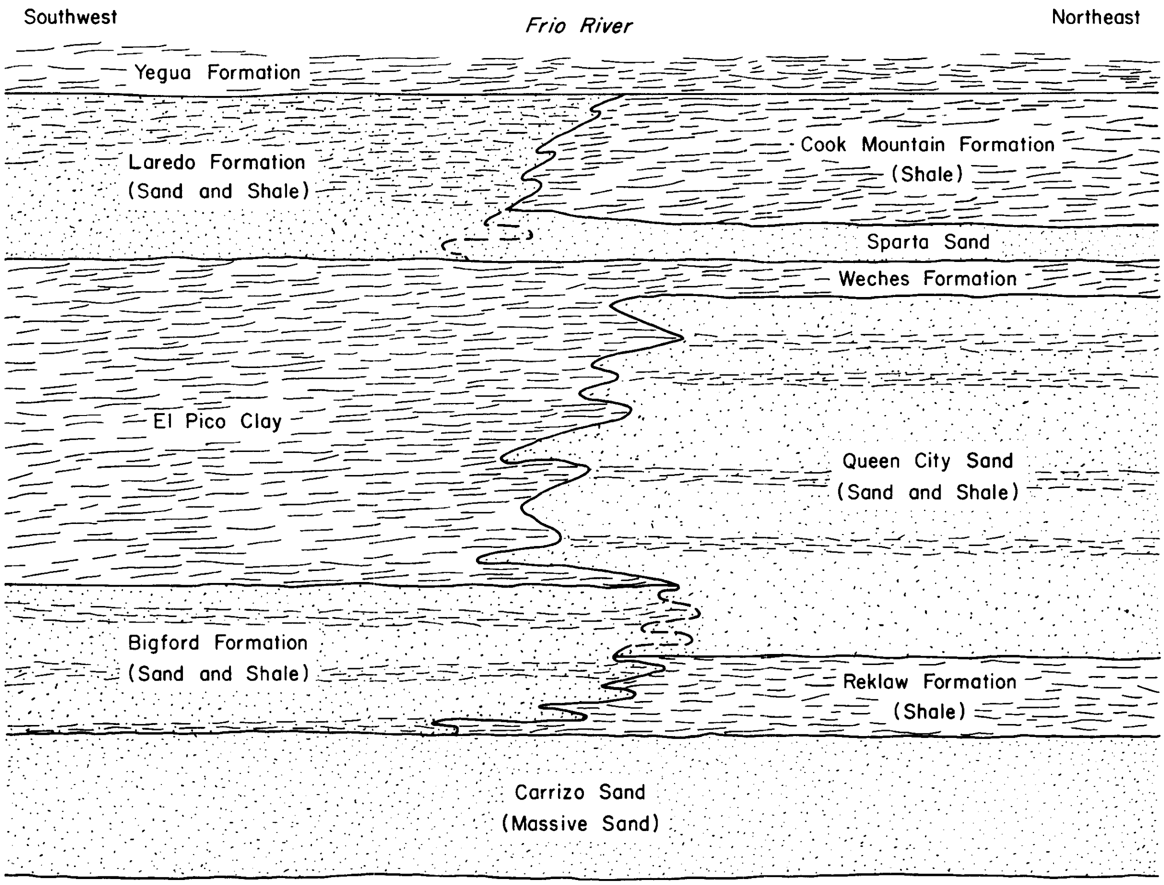


Figure 2

Extent of Fresh to Slightly Saline Water in the Carrizo-Wilcox Aquifer the term "Carrizo-Wilcox aquifer" is often used. The waters probably comingle to a degree, although most of the sand beds in the Wilcox Group are less permeable and most contain poorer quality water than the Carrizo Sand. Within the Wilcox, also, water quality in most areas generally diminishes with greater depth. The depth to and altitude of the base of fresh to slightly saline water in the Carrizo-Wilcox aquifer (Carrizo Sand and Wilcox Group) are shown on Figure 11. A better understanding of the extent of fresh to slightly saline water in the aquifer can be had by referring to the geohydrologic sections (Figures 27, 28, and 29). The total saturated thickness, and net saturated sand thickness, of the Carrizo-Wilcox aquifer above the base of fresh to slightly saline water are illustrated in Figure 12.

Above the Carrizo in areas west and southwest of the Frio River are the Bigford, El Pico Clay, Laredo, and Yegua Formations, which differ in lithologic character and fossil content from their equivalent counterparts northeast of the Frio River—the Reklaw, Queen City Sand, Weches, Sparta Sand, and Cook Mountain. Nomenclature of these and other formations of the Claiborne Group is detailed by Eargle (1968). The predominantly sandy units—the Queen City Sand, Bigford Formation, Sparta Sand, and Laredo Formation—interfinger in the vicinity of the Frio River to form two aquifers. These are the Queen City-Bigford and the Sparta-Laredo aquifers, which yield fresh to slightly saline water in the study area. The interfingering relationships of the formations in the vicinity of the Frio River are illustrated in Figure 3.

The Queen City-Bigford aquifer includes the water-bearing sands of the Queen City Sand and Bigford Formation. The Bigford Formation consists of sand, silt, and thin beds of shale, with the shale making up about 25 percent of the formation in the outcrop (Eargle, 1968). The Queen City Sand is a thick unit of sand, clay, and sandy clay. The Queen City-Bigford aquifer ranges in thickness from approximately 200 feet in Zavala



Modified from Eargle (1968)

Figure 3.—Idealized Geologic Section Illustrating the Interfingering of Sands and Shales of the Claiborne Group in the Vicinity of the Frio River

County to 1,400 feet in Frio County. Figure 4 shows the general extent of fresh to slightly saline water in the Queen City-Bigford aquifer in the study area.

The Sparta-Laredo aquifer contains the water-bearing sands of the Sparta Sand and Laredo Formation. The Sparta Sand ranges from 40 to 200 feet in thickness and consists of sand with minor amounts of clay. The Laredo Formation, consisting of sand and sandstone at the base and grading into sandy clay and clay at the top, attains a maximum thickness of 600 to 700 feet. The general extent of fresh to slightly saline water in the Sparta-Laredo aquifer in the study area is shown in Figure 5.

The uppermost formation of the Claiborne Group is the Yegua, consisting of fine sand, silt, and clay. The Yegua Formation generally yields small amounts of slightly to moderately saline water (1,000 to 10,000 mg/l dissolved solicls) east of the Frio River. West of the Frio River, the Yegua yields highly mineralized water that is generally unfit for livestock use.

THE CARRIZO AQUIFER

The name “Carrizo” was first applied by Owen (1889) to the thick, massive sand beds that unconformably overlie the sand, silt, and clay of the Wilcox Group in the vicinity of Carrizo Springs, Texas. Plummer (Sellards, Adkins, and Plummer, 1932) suggests that the type locality for the Carrizo Sand be designated at Brand Rock on the east bank of Pena Creek, which is about 5 miles west of Carrizo Springs. The development of the Carrizo aquifer dates back to 1884 when S. D. Frazier completed the first flowing well at Carrizo Springs in Dimmit County at a depth of 165 feet (Roesler, 1890). Today, the Carrizo aquifer is the most prolific source of fresh ground water in the Winter Garden Area.

Recharge, Discharge, and Movement

Annual recharge to the Carrizo aquifer in Dimmit, Zavala, and Maverick Counties according to Turner and others (1948) averages about 25,000 acre-feet. Alexander and White (1966) estimated the annual average recharge to the Carrizo aquifer in Atascosa and Frio Counties to be 13,000 and 10,000 acre-feet, respectively. Barnes (1956) reported approximately 26,000 acre-feet per year being recharged in Wilson County. These areas account for about 75 percent of the Carrizo outcrop in the Winter Garden Area. From these data it was estimated that the remaining outcrop areas would receive about 26.000 acre-feet annually, based upon the higher permeability of the aquifer and the higher amount of precipitation in the eastern portion of the study area. Thus, the average rate of recharge to the Carrizo aquifer in the Winter Garden Area is about 100,000 acre-feet per year or 89 mgd (million gallons per day).

In some local areas of the Carrizo aquifer’s extent, some of the sands containing fresh to slightly saline water in the Wilcox Group, Bigford Formation, and Reklaw Formation may be hydrologically connected with the Carrizo Sand. Leakage into the Carrizo aquifer is known to occur in the regions of intensive irrigation in Dimmit, Frio, and Zavala Counties where water of higher mineral content in other formations leaks through confining beds or percolates down well bores of poorly constructed and abandoned wells. Computer simulations of the aquifer, which will be discussed later, have indicated that much greater water-level declines should have occurred during the period 1963-1969 than actually occurred except as may be accounted for by interformational leakage. The computer simulations indicate that about 9,500 acre-feet per year (8.5 mgd) leaked into the Carrizo during the period 1963-1969.

The estimated amount of water pumped for irrigation, public supply, and industrial use from the Carrizo aquifer in the study region and in the Winter Garden District (Dimmit, Zavala, and eastern Maverick Counties) is given in Figure 7. The graph shows that pumpage in the Winter Garden Area averaged about 272,000 acre-feet per year (243 mgd) for the period 1963-I 969.

Ground water in the Carrizo aquifer moves downward from the recharge zone to the zone of saturation and then generally in the direction of the slope of the piezometric surface. The piezometric surface is an imaginary surface that everywhere coincides with the static water level in the aquifer. The piezometric surfaces of the Carrizo aquifer in 1929-30 and in 1970 are illustrated in Figures 13 and 14, respectively.

Hydraulic Characteristics

An aquifer’s hydraulic characteristics are generally described in terms of its coefficients of transmissibility and storage. These were determined for the Carrizo aquifer by conducting pumping tests in selected wells, and from the well performance tests that had been made by water well drilling and servicing companies. The tests consist of pumping a well for a period of time and taking periodic water-level measurements in the pumping well and in one or more nearby observation wells if available.

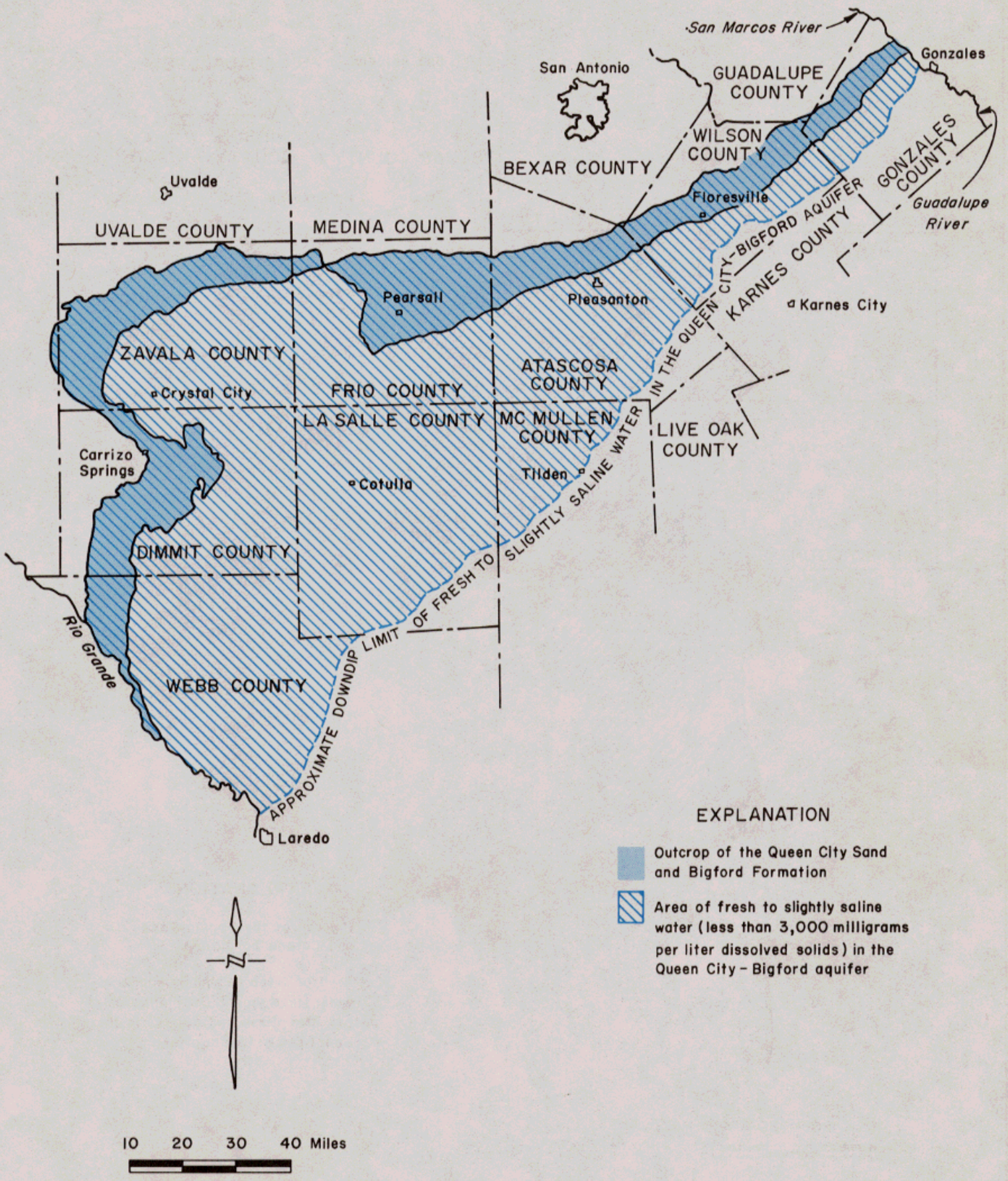


Figure 4

Extent of Fresh to Slightly Saline Water in the Queen City-Bigford Aquifer

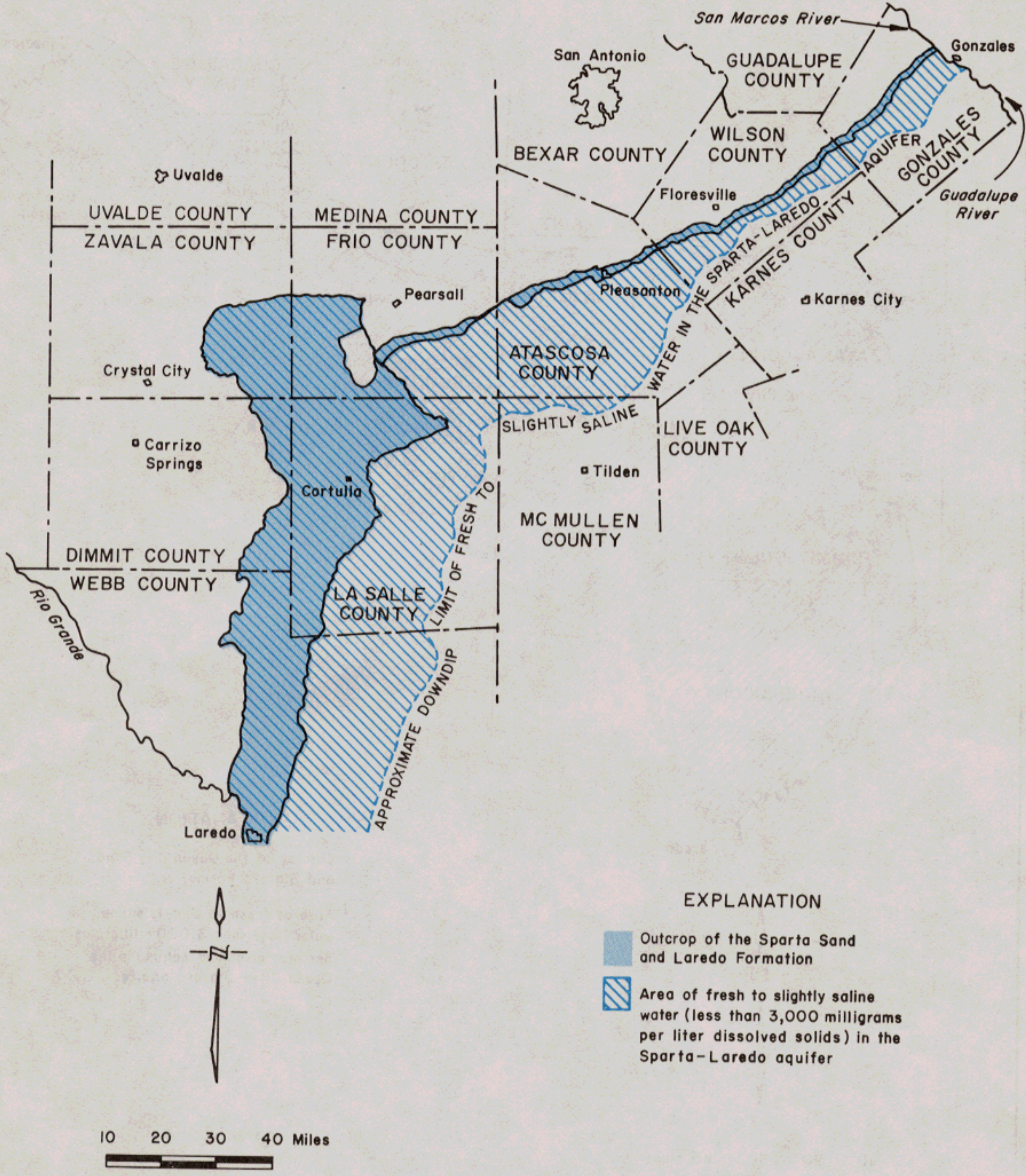


Figure 5
Extent of Fresh to Slightly Saline Water in the Sparta-Laredo Aquifer

Data obtained from pumping tests were analyzed using the Theis (1935) nonequilibrium formula. For tests conducted under water-table conditions, the water-level drawdown data were corrected in the manner described by Jacob (1944) for the decrease in aquifer transmissibility that accompanies the decrease in its saturated thickness during the test. Performance test data were analyzed by the modified Thiem formula as presented by Thomasson (1960) and with further modification by the authors to consider well completion efficiencies. Specific capacities of wells were also determined, by dividing the well's yield by the total water-level drawdown measured in the well.

Each well test provided transmissibility data for only that portion of the aquifer screened by the well. These transmissibility values were divided by the effective sand thickness utilized by the well, to obtain a coefficient of aquifer permeability. The permeability coefficients were then multiplied by an estimate of the aquifer's total net thickness of sand containing fresh to slightly saline water to obtain approximate coefficients of transmissibility for the aquifer's total fresh to slightly saline water section.

The coefficients of permeability determined for the aquifer are shown in Figure 15, and the coefficients of transmissibility are given in Figure 16. The specific capacities of individual water wells are given in Figure 17.

The largest permeability and transmissibility coefficients found in selected counties are presented below:

COUNTY	MAXIMUM COEFFICIENT OF PERMEABILITY (GPD/FT^2 AT FORMATION TEMPERATURE)	MAXIMUM COEFFICIENT OF TRANSMISSIBILITY (GPD/FT AT FORMATION TEMPERATURE)
Atascosa	475	317,000
Dimmit	410	65,000
Frio	500	230,000
Gonzales	300	200,000
La Salle	170	110,000
McMullen	90	100,000
Webb	70	7,000
Wilson	500	301,000
Zavala	425	75,000

The average coefficient of storage in the outcrop, under water-table conditions, is approximately 0.25. Downdip, where the aquifer is under artesian conditions, the average coefficient of storage is approximately 5 X 10^{-4} or 0.0005. The coefficient of storage is a dimensionless term which indicates the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. For water-table conditions the coefficient of storage is the same as the specific yield of the material dewatered during pumping, and for artesian conditions it reflects the amount of aquifer compression and water expansion when the head or pressure is reduced during pumping.

An aquifer's permeability depends on the shape, sorting, arrangement, and cementation of its component sediment grains. To obtain permeability data for the Carrizo aquifer in the outcrop, a test-hole drilling program was initiated. Test holes were drilled with the Texas Water Development Board's drilling rig in the outcrop of the Carrizo Sand in seven counties, and the cores obtained from these test holes were analyzed by the Board's Materials Testing Laboratory to obtain information on sand particle diameters and to determine coefficients of grain-size uniformity and permeability. Permeability coefficients, in gallons per day per square foot (gpd/ft^2), were determined by using a falling head permeameter and correcting the results to 60°F (16°C).

The results of laboratory determinations for selected test holes in the Carrizo Sand outcrop are summarized by county below. The coefficients of permeability shown are generally higher than those obtained from analyses of pumping tests of wells in the Carrizo Sand outcrop.

COUNTY	NUMBER OF TEST HOLES	AVERAGE SAND GRAIN DIAMETER 50 PERCENT RETAINED (INCHES)	AVERAGE SAND GRAIN DIAMETER 90 PERCENT RETAINED (INCHES)	AVERAGE UNIFORMITY COEFFICIENT	AVERAGE COEFFICIENT OF PERMEABILITY (GPD/FT^2 AT 60°F)	
					CORES	CUTTINGS
Atascosa	2	0.0115	0.0066	2.00	487	555
Dimmit	1	.0092	.0048	2.09	40	479
Frio	1	.0106	.0064	1.82	–	
Maverick	1	.0122	.0063	2.24	–	685
Medina	2	.0086	.0051	1.85	748	626
Wilson	4	.009 1	.0047	2.11	475	556
Zavala	4	.0088	.0055	1.72	944	539

Chemical Quality

All ground water contains minerals carried in solution, the type and concentration of which depend upon the surface and subsurface environment, rate of ground-water movement, and source of the ground water. Precipitation is relatively free of minerals until it comes in contact with the various constituents which make up the soils and component rocks of the aquifer. As a result of the water's solvent power, minerals are dissolved and carried into solution as the water moves through the aquifer. The concentration depends upon the solubility of the minerals present, the length of time water is in contact with the rocks, and the amount of dissolved carbon dioxide the water contains. Concentrations of dissolved minerals in ground water generally increase with depth where circulation has been restricted due to various geologic conditions.

The source, significance, and range in concentration of selected chemical constituents in ground water in the Carrizo aquifer are given in Table 2. Dissolved-solids concentrations and sodium adsorption ratios (SAR) in water samples collected from the Carrizo aquifer are illustrated in Figures 18 and 19.

The characteristics of an irrigation water that seem to be most important in determining its quality are as follows: (a) total concentration of soluble salts; (b) relative proportion of sodium to other principal cations (magnesium, calcium, and potassium); (c) concentration of boron or other elements that may be toxic; and (d) under some conditions, the bicarbonate concentration as related to the concentration of calcium plus magnesium. These have been termed, respectively, the salinity hazard, the sodium (alkali) hazard, the boron hazard, and the bicarbonate ion hazard.

For the purposes of diagnosis and classification of irrigation waters, the total concentration of soluble salts (salinity hazard) in the water can be adequately expressed in terms of specific conductance. Specific conductance is the measure of the ability of the ionized inorganic salts in solution to conduct an electrical current and is usually expressed in terms of micromhos per cubic centimeter at 25°C. In general, water having a conductance below 750 micromhos per cubic centimeter is satisfactory for irrigation; however, salt-sensitive crops, such as strawberries and green beans, may be adversely affected by irrigation water having a conductance in the range of 250 to 750 micromhos per cubic centimeter. The specific conductance of water samples collected from the Carrizo aquifer ranged from 94 to 4,990 micromhos per cubic centimeter at 25°C.

In the past, irrigation waters were divided into the three following classes based on the percent sodium: (a) water with a percent sodium less than 60, excellent

Table 2.—Source, Significance, and Concentration Range of Selected Chemical Constituents in Ground Water in the Carrizo Aquifer

(Concentration ranges shown are in milligrams per liter except specific conductance, pH, percent sodiu sodium-adsorption ratio, and residual sodium carbonate.)

CONSTITUENT OR PROPERTY	SOURCE OR CAUSE	SIGNIFICANCE	CONCENTRATION RANGE
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 mg/l. High concentrations, as much as 100 mg/l, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type water softeners.	4 - 95
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment.	On exposure to air, iron in ground water oxidizes to reddish-brown precipitate. More than about 0.3 mg/l stains laundry and utensils reddish-brown. Objectionable for food processing, textile processing, beverages, ice manufacture, brewing, and other processes. U.S. Public Health Service (1962) drinking-water standards state that iron should not exceed 0.3 mg/l. Larger quantities cause unpleasant taste and favor growth of iron bacteria.	<1 - 68.62
Calcium (Ca) and Magnesium (Mg)	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.	(Ca) 2 - 323 (Mg) <1 - 103
Sodium (Na) and Potassium (K)	Dissolved from practically all rocks and soils. Found also in oil-field brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefullness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.	(Na) 8 - 1,310 (K) <1 - 23
Bicarbonate (HCO_3) and Carbonate (CO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.	(HCO_3) <1 - 2,760
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. U.S. Public Health Service (1962) drinking-water standards recommend that the sulfate content should not exceed 250 mg/l.	<1 - 1,160

Table 2.—Source, Significance, and Concentration Range of Selected Chemical Constituents in Ground Water in the Carrizo Aquifer—Continued

CONSTITUENT OR PROPERTY	SOURCE OR CAUSE	SIGNIFICANCE	CONCENTRATION RANGE
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in oil-field brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. U.S. Public Health Service (1962) drinking-water standards recommend that the chloride content should not exceed 250 mg/l.	.9 - 970
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils. Added to many waters by fluoridation of municipal supplies.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth depending on the concentration of fluoride, the age of the child, amount of drinking water consumed, and susceptibility of the individual (Maier, 1950, p. 1120-1132).	<1 - 10.7
Nitrate (NO_3)	Decaying organic matter, sewage, fertilizers, and nitrates in soil.	Concentration much greater than the local average may suggest pollution. U.S. Public Health Service (1962) drinking-water standards suggest a limit of 45 mg/l. Waters of high nitrate content have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding (Maxcy, 1950, p. 271). Nitrate has been shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.	<1 - 120
Boron (B)	A minor constituent of rocks and of natural waters.	An excessive boron content will make water unsuitable for irrigation. Wilcox (1955, p. 11) indicated that a boron concentration of as much as 1.0 mg/l is permissible for irrigating sensitive crops; as much as 2.0 mg/l for semitolerant crops; and as much as 3.0 mg/l for tolerant crops. Crops sensitive to boron include most deciduous fruits and nut trees and navy beans; semitolerant crops include most small grains, potatoes and some other vegetables, and cotton; and tolerant crops include alfalfa, most root vegetables, and the date palm.	<1 - 1.5
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils.	U.S. Public Health Service (1962) drinking-water standards recommend that waters containing more than 500 mg/l dissolved solids not be used if other less mineralized supplies are available. For many purposes the dissolved-solids content is a major limitation on the use of water. A general classification of water based on dissolved-solids	6 - 3,139

Table 2.—Source, Significance, and Concentration Range of Selected Chemical Constituents in Ground Water in the Carrizo Aquifer—Continued

CONSTITUENT OR PROPERTY	SOURCE OR CAUSE	SIGNIFICANCE	CONCENTRATION RANGE
		content, in mg/l, is as follows (Winslow and Kister, 1956, p. 5): Waters containing less than 1,000 mg/l of dissolved solids are considered fresh; 1,000 to 3,000 mg/l, slightly saline; 3,000 to 10,000 mg/l, moderately saline; 10,000 to 35,000 mg/l, very saline; and more than 35,000 mg/l, brine.	
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. Waters of hardness up to 60 mg/l are considered soft; 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; and more than 180 mg/l, very hard.	1 - 2,027
Specific conductance (micromhos per cubic centimeter at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.	94 - 4,990
Hydrogen ion concentration (pH)	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals.	3.3 - 8.8
Percent sodium (% Na)	Sodium in water.	A ratio (using milliequivalents per liter) of the sodium ions to the total sodium, calcium, and magnesium ions. A sodium percentage exceeding 50 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.	2.0 - 99.7
Sodium-adsorption ratio (SAR)	Sodium in water.	A ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with soil (U.S. Salinity Laboratory Staff, 1954, p. 72, 156). Defined by the following equation: $SAR = \frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$, where Na^+, Ca^{++}, and Mg^{++} represent the concentrations, in milliequivalents per liter (me/l), of the respective ions.	.06 - 161.28

Table 2.—Source, Significance, and Concentration Range of Selected Chemical Constituents in Ground Water in the Carrizo Aquifer—Continued

CONSTITUENT OR PROPERTY	SOURCE OR CAUSE	SIGNIFICANCE	CONCENTRATION RANGE
Residual sodium carbonate (RSC)	Sodium and carbonate or bicarbonate in water.	As calcium and magnesium precipitate as carbonates in the soil, the relative proportion of sodium in the water is increased (Eaton, 1950, p. 123-133). Defined by the following equation: $RSC = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++})$, where CO_3^{--}, HCO_3^{-}, Ca^{++}, and Mg^{++} represent the concentrations, in milliequivalents per liter (me/l), of the respective ions.	<1 - 45.02

to good; (b) water with a percent sodium between 60 and 75, good to injurious, and (c) water with a percent sodium greater than 75, injurious to unsatisfactory. The percent sodium in water samples collected from the Carrizo aquifer ranged from 2.0 to 99.7.

A better measure of the sodium hazard of water for irrigation is the sodium-adsorption ratio (SAR) which is used to express the relative activity of sodium ions in exchange reactions with soil. The SAR is easily computed from the data determined in the usual water analysis by using the following equation:

$$SAR = \frac{Na^{+}}{\sqrt{\dfrac{Ca^{++} + Mg^{++}}{2}}},$$

where Na^{+}, Ca^{++}, and Mg^{++} represent the concentrations of sodium, calcium, and magnesium ions in milliequivalents per liter (me/l). The SAR of water samples collected from the Carrizo aquifer ranged from 0.06 to 161.28.

When the SAR and the specific conductance of a water are known, the classification of the water for irrigation can be determined by graphically plotting these values on the diagram shown in Figure 6. Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. Medium-sodium water (S2) will present an appreciable sodium hazard in certain fine-textured soils having high cation-exchange capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils having good permeability. High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management such as good drainage, leaching, and addition of organic matter. Very

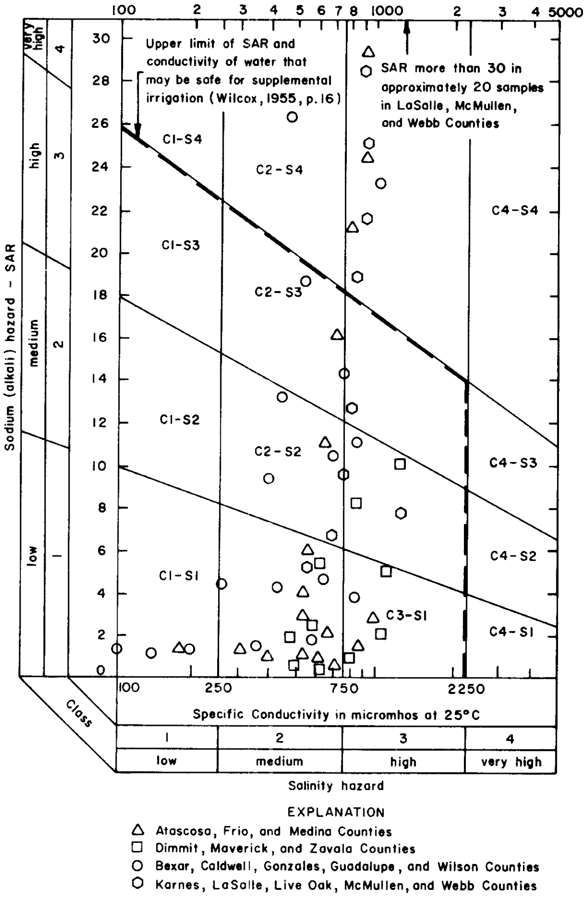


Figure 6.—Classification of Irrigation Waters, and Quality of Water From Representative Wells in the Carrizo Aquifer (After U.S. Salinity Laboratory Staff, 1954, p. 80)

high sodium water (S4) is generally unsatisfactory for irrigation unless special action is taken, such as addition of gypsum to the soil.

Low-salinity water (Cl) can be used for irrigation of most crops on most soils with little likelihood that soil salinity will develop. Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. High salinity water (C3) cannot be used on soils with restricted drainage.

The classification of ground water from representative wells completed in the Carrizo aquifer, sampled throughout the Winter Garden Area, shows low to high salinity hazard (specific conductivity 100 to 1,300 micromhos per cubic centimeter at 25°C) while the sodium (alkali) hazard is generally low to medium (SAR 0.06 to 13) as illustrated in Figure 6.

In appraising the quality of an irrigation water, first consideration must be given to salinity and sodium hazards (Figure 6). Then consideration should be given to independent characteristics such as boron and bicarbonate, either of which may change the quality rating. The use of water of any quality must take into account such factors as land and crop management practices and soil drainage.

In the Winter Garden Area most public and domestic ground-water supplies are obtained from the Carrizo aquifer. Concentration limits recommended by the U.S. Public Health Service (1962, p. 7-8) for chemical constituents in public and domestic water supplies are shown in the following table. It should be noted that these concentration limits will prevail except where suitable water supplies are not available or cannot be made available at a reasonable cost.

SUBSTANCE		CONCENTRATION (MG/L)
Chloride	(Cl)	250
Fluoride	(F)	.8*
Iron	(Fe)	.3
Manganese	(Mn)	.05
Nitrate	(NO^3)	45
Sulfate	(SO_4)	250
Dissolved-solids		500

*Upper limit based on annual average of maximum daily air temperature range of 79.3 – 90.5ºF. The recommended control limits of fluoride concentration in mg/l are: lower, 0.6; optimum, 0.7; and upper, 0.8.

Water samples from wells completed in the Carrizo aquifer were examined for chloride, sulfate, and dissolved solids. The chloride content ranged from 0.9 to 970 mg/l in 819 samples; only 5 percent of the samples contained water having greater than 250 mg/l chloride. Sulfate content ranged from less than 1 to 1,160 mg/l in 807 samples; only 4 percent of the samples contained water having greater than 250 mg/l sulfate. The dissolved-solids content in Carrizo aquifer samples ranged from 6 to 3,139 mg/l in 772 samples; only 18 percent of the samples contained water having greater than 500 mg/l dissolved solids.

Water containing less than 1,000 mg/l of dissolved solids is regarded in this report as fresh and more than 1,000 mg/l as saline. Less than 500 mg/l is recommended by the U.S. Public Health Service (1962) in potable water where water of this quality is available. However, it must be recognized that in many areas of Texas the only available water supply may have a dissolved-solids concentration greatly in excess of 1,000 mg/l. Only 7 percent of the Carrizo samples contained water having more than 1,000 mg/l dissolved solids.

Water having a dissolved-solids concentration of 1,000 to 3,000 mg/l is classified as slightly saline and is used by many small communities, farms, and ranches. Water of this class has been recognized as somewhat unsatisfactory but generally not harmful. Less than 1 percent of the Carrizo wells within the Winder Garden Area contained water having greater than 3,000 mg/l dissolved solids.

The chemical quality of ground water from the Carrizo aquifer is generally favorable for industrial use throughout most of the Winter Garden Area. The tolerance in chemical quality of water for industrial use differs widely for different industries and different processes. Table 3 illustrates some of the suggested tolerances for a number of industries (American Water Works Association, 1950, p. 66-67).

Aquifer Development and the Decline of Water Levels

Development of ground water from the Carrizo aquifer in the Winter Garden Area prior to 1900 was mainly for domestic, livestock, and public supply purposes. One of the earlier irrigation wells was completed at Carrizo Springs, Dimmit County, in 1884, at a depth of 165 feet. This was a flowing well that was used for both domestic and irrigation purposes (Roesler, 1890). During the period 1900-1930, large-scale irrigation development took place in Dimmit and Zavala Counties due to introduction of the efficient deep-well turbine pump. Later irrigation development spread northeast to many of the other counties in the Winter Garden Area.

Pumpage from the Carrizo aquifer during 1930-1969 is shown in Figure 7. The pumpage data in Figure 7 are based in part on power and yield tests conducted on selected irrigation wells, in part on questionnaires mailed annually by the Texas Water Development Board to municipalities and industries, and in part on various earlier studies in the region. The amount of ground water pumped from the Carrizo

Table 3.—Water-Quality Tolerances for Industrial Applications[1]

[Allowable Limits in Milligrams Per Liter Except as Indicated]

INDUSTRY	TURBIDITY	COLOR	COLOR $+O_2$ CONSUMED	DISSOLVED OXYGEN (ml/l)	ODOR	HARDNESS	ALKALINITY (AS $CaCO_3$)	pH	TOTAL SOLIDS	Ca	Fe	Mn	Fe+Mn	Al_2O_3	SiO_2	Cu	F	CO_3	HCO_3	OH	$CaSO_4$	Na_2SO_4 TO Na_2SO_3 RATIO	GENERAL[2]
Air Conditioning[3]	--	--	--	--	--	--	--	--	--	--	0.5	0.5	0.5	--	--	--	--	--	--	--	--	--	A,B
Baking	10	10	--	--	--	(4)	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	C
Boiler feed:																							
0-150 psi	20	80	100	2	--	75	--	8.0+	3,000-1,000	--	--	--	--	5	40	--	--	200	50	50	--	1 to 1	--
150-250 psi	10	40	50	.2	--	40	--	8.5+	2,500-500	--	--	--	--	.5	20	--	--	100	30	40	--	2 to 1	--
250 psi and up	5	5	10	0	--	8	--	9.0+	1,500-100	--	--	--	--	.05	5	--	--	40	5	30	--	3 to 1	--
Brewing:[5]																							
Light	10	--	--	--	Low	--	75	6.5-7.0	500	100-200	.1	.1	.1	--	--	--	1	--	--	--	100-200	--	C,D
Dark	10	--	--	--	Low	--	150	7.0+	1,000	200-500	.1	.1	.1	--	--	--	1	--	--	--	200-500	--	C,D
Canning:																							
Legumes	10	--	--	--	Low	25-75	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	C
General	10	--	--	--	Low	--	--	--	--	--	.2	.2	.2	--	--	--	1	--	--	--	--	--	C
Carbonated beverages[6]	2	10	10	--	0	250	50	--	850	--	.2	.2	.3	--	--	--	.2	--	--	--	--	--	C
Confectionary	--	--	--	--	Low	--	--	(7)	100	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--
Cooling [8]	50	--	--	--	--	50	--		--	--	.5	.5	.5	--	--	--	--	--	--	--	--	--	A,B
Food, general	10	--	--	--	Low	--	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	C
Ice (raw water) [9]	1-5	5	--	--	--	--	30-50	--	300	--	.2	.2	.2	--	10	--	--	--	--	--	--	--	C
Laundering	--	--	--	--	--	50	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--
Plastics, clear, undercolored	2	2	--	--	--	--	--	--	200	--	.02	.02	.02	--	--	--	--	--	--	--	--	--	--
Paper and pulp: [10]																							
Groundwood	50	20	--	--	--	180	--	--	--	--	1.0	.5	1.0	--	--	--	--	--	--	--	--	--	A
Kraft pulp	25	15	--	--	--	100	--	--	300	--	.2	.1	.2	--	--	--	--	--	--	--	--	--	--
Soda and sulfite	15	10	--	--	--	100	--	--	200	--	.1	.05	.1	--	--	--	--	--	--	--	--	--	--
Light paper, HL-Grade	5	5	--	--	--	50	--	--	200	--	.1	.05	.1	--	--	--	--	--	--	--	--	--	B
Rayon (viscose) pulp:																							
Production	5	5	--	--	--	8	50	--	100	--	.05	.03	.05	<8.0	<25	<5	--	--	--	--	--	--	--
Manufacture	.3	--	--	--	--	55	--	7.8-8.3	--	--	.0	.0	.0	--	--	--	--	--	--	--	--	--	--
Tanning [11]	20	10-100	--	--	--	50-135	135	8.0	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--
Textiles:																							
General	5	20	--	--	--	20	--	--	--	--	.25	.25	--	--	--	--	--	--	--	--	--	--	--
Dyeing [12]	5	5-20	--	--	--	20	--	--	--	--	.25	.25	.25	--	--	--	--	--	--	--	--	--	--
Wool scouring[13]	--	70	--	--	--	20	--	--	--	--	1.0	1.0	1.0	--	--	--	--	--	--	--	--	--	--
Cotton bandage[13]	5	5	--	--	Low	20	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--

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[1] American Water Works Association, 1950.

[2] A—No corrosiveness; B—No slime formation; C—Conformance to Federal drinking water standards necessary; D-NaCl, 275 mg/l.

[3] Waters with algae and hydrogen sulfide odors are most unsuitable for air conditioning.

[4] Some hardness desirable.

[5] Water for distilling must meet the same general requirements as for brewing (gin and spirits mashing water of light-beer quality; whiskey mashing water of dark-beer quality).

[6] Clear, odorless, sterile water for syrup and carbonization. Water consistent in character. Most high quality filtered municipal water not satisfactory for beverages.

[7] Hard candy requires pH of 7.0 or greater, as low value favors inversion of sucrose, causing sticky product.

[8] Control of corrosiveness is necessary as is also control of organisms, such as sulfur and iron bacteria, which tend to form slimes.

[9] Ca $(HCO_3)_2$ particularly troublesome. $Mg(HCO_3)_2$ tends to greenish color. CO_2 assists to prevent cracking. Sulfates and chlorides of Ca, Mg, Na should each be less than 300 mg/l (white butts).

[10] Uniformity of composition and temperature desirable. Iron objectionable as cellulose adsorbs iron from dilute solutions. Manganese very objectionable, clogs pipelines and is oxidized to permanganates by chlorine, causing reddish color.

[11] Excessive iron, manganese, or turbidity creates spots and discoloration in tanning of hides and leather goods.

[12] Constant composition; residual alumina 0.5 mg/l.

[13] Calcium, magnesium, iron, manganese, suspended matter, and soluble organic matter may be objectionable.

Table 4.-Estimated Use of Ground Water for Irrigation, Public Supply, and Industrial Purposes From the Carrizo-Wilcox, Queen City-Bigford, and Sparta-Laredo Aquifers, 1969

AQUIFER	PUMPAGE, IN ACRE-FEET			
	PUBLIC SUPPLY	INDUSTRIAL	IRRIGATION	TOTAL'
Carrizo-Wilcox	–	–	–	273,000
a) Carrizo	8,900	3,100	255,000	–
b) Wilcox	2,000	480	3,700	–
Queen City-Bigford	1,100	31	4,000	5,130
Sparta- Laredo	120	–	850	97
			Total *	279,000

*Figures are approximate because some of the pumpage is estimated. Totals are rounded to three significant figures. In addition to the amounts shown in the table, approximately 3,000 acre-feet was lost from uncontrolled flowing wells and approximately 11,000 acre-feet was used for domestic and livestock purposes from these aquifers.

aquifer from 1930 to 1938 remained nearly constant. Since the late 1930's or early 1940's, the aquifer has undergone generally steady development to provide increasingly larger amounts of ground water, mostly for irrigation needs. Other causes for this increase include population growth, industrial expansion, and widespread drought conditions in early 1950's.

Table 4 provides estimates of the amounts of ground water obtained from the Carrizo and other aquifers in 1969 in the Winter Garden Area. The total irrigation, public supply, and industrial ground-water pumpage in 1969 in the Winter Garden Area was approximately 279,000 acre-feet or 249 mgd. Irrigation pumpage accounted for about 264,000 acre-feet (235 mgd), with about 255,000 acre-feet (228 mgd) coming from the Carrizo aquifer. These figures indicate that the Carrizo aquifer supplied 97 percent of the total irrigation pumpage, and that the irrigation pumpage amounts to 95 percent of the total irrigation, public supply, and industrial ground-water pumpage of the Winter Garden Area.

Large Carrizo water-level declines have taken place in the Winter Garden District (Dimmit, Zavala, and eastern Maverick Counties) where large amounts of ground water have been used in the production of garden vegetables. Figure 20 shows declines of 240 feet in this area for the period 1929-30 to 1970. Water-level declines in Atascosa, Wilson, and Gonzales Counties have not been as severe as in the Winter Garden District; however, south of Pearsall in Frio County, water levels have declined approximately 180 feet during this same period.

Availability of Ground Water for Future Development

Application of the Digital Computer Mathematical Model

One of the primary objectives of this study was to simulate the Carrizo aquifer in the Winter Garden Area with a digital computer mathematical model. The simulation process allows the prediction of water-level declines in the Carrizo aquifer based on projected pumpage, and the predicted water-level declines provide a means for evaluating the ability of the Carrizo aquifer to meet anticipated ground-water withdrawal requirements.

Three sets of aquifer simulations were made with the Carrizo aquifer model. First, the model was provided with data on the estimated past and projected future pumping rates and was programmed to compute and print out the amounts of resulting water-level decline for the periods 1970-l 980, 1970-l 990, and 1970-2020. County Agricultural Extension Agents furnished projections of irrigation pumpage requirements for these periods and studies conducted by the Board were used to project public supply and industrial

The following table summarizes the average annual pumpage that was programmed into the model for the periods 1963-1970, 1970-1980, 1980-1990, and 1990-2020:

PERIOD	FRIO COUNTY		WINTER GARDEN DISTRICT (DIMMIT, ZAVALA, AND EASTERN MAVERICK COUNTIES)		WINTER GARDEN AREA (REPORT AREA)	
	ACRE-FEET PER YEAR	MGD	ACRE-FEET PER YEAR	MGD	ACRE-FEET PER YEAR	MGD
1963-1970	72,700	64.86	121,400	108.31	272,000	242.65
1970-1980	74,200	66.20	120,600	107.59	306,000	272.99
1980-1990	76,300	68.06	119,600	106.69	314,000	280.12
1990-2020	79,000	70.48	119,000	106.16	332,000	296.19

Recharge and leakage to the Carrizo aquifer were assumed for these studies to approximate 100,000 acre-feet per year (89 mgd) and 9,500 acre-feet per year (8.5 mgd), respectively, in the Winter Garden Area.

Next, it was desired to know whether the Carrizo aquifer southeast of San Antonio in Wilson County could provide a firm municipal water supply of 20,000 to 40,000 acre-feet per year (18 to 36 mgd) for the San Antonio metropolitan area. The model was made to simulate two alternative lines of pumping wells or well fields, one under water-table conditions (Line A, shown on Figure 24) and the other under artesian conditions (Line B, shown on Figure 25). Wells along Line A were placed just southeast of the outcrop of the Carrizo Sand. Those along Line B were located approximately 5 miles downdip from the outcrop. Each of these lines of wells was simulated to produce 20,000 acre-feet per year (18 mgd), 30,000 acre-feet per year (27 mgd), and 40,000 acre-feet per year (36 mgd). This pumpage was in addition to the predicted irrigation, public supply, and industrial pumpage which had been forecast for the Winter Garden Area. Recharge to the Carrizo aquifer in the area of investigation was estimated to be approximately 26,000 acre-feet annually (23 mgd). This recharge area includes the Carrizo Sand outcrop in Wilson County and parts of Atascosa, Bexar, and Guadalupe Counties.

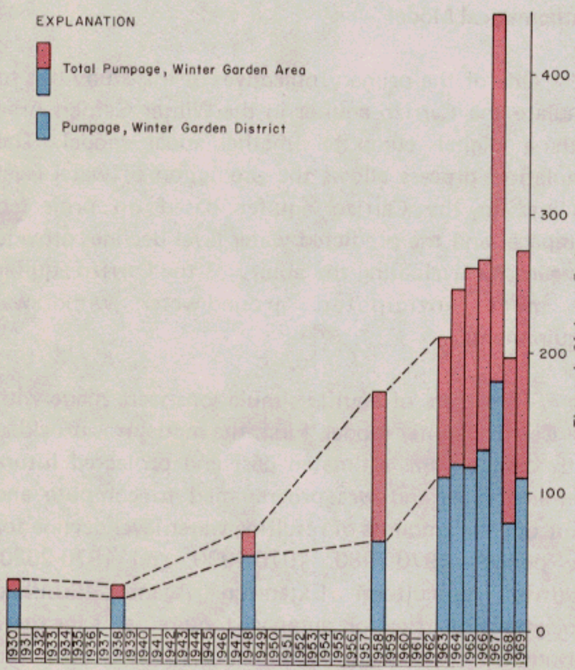

Figure 7.—Approximate Pumpage From the Carrizo Aquifer for Irrigation, Public Supply, and Industrial Use, 1930-1969

Last, simulations were made with the aquifer model to determine the annual withdrawal or pumping rate per unit area which would lower the Carrizo aquifer water levels to 400 feet below land surface throughout the Winter Garden Area. The pumping and lowering of water levels would occur from 1970 to 2020 and generally in the area between the outcrop and the downdip limit of fresh to slightly saline water (less than 3,000 mg/l dissolved solids). For the purpose of this study, ground-water development of the Carrizo aquifer in the downdip areas was considered economically feasible as long as water levels were 400 feet or less below land surface. Under these conditions, the following criteria were used as a basis for data input into the model prior to the simulation: (a) recharge and leakage to the Carrizo aquifer were assumed to approximate 100,000 acre-feet per year (89 mgd) and 9,500 acre-feet per year (8.5 mgd), respectively; (b) in the area where the Carrizo aquifer contains water having a dissolved-solids content greater than 1,000 mg/l, pumpage was not increased above the 1963-1969 average; and (c) pumpage was regulated so that water-level declines would be minimized in the outcrop and not fall below the top of the aquifer in the downdip area. The simulation provided data in the form of annual pumpage rates per unit area, which were used to determine the areas where the Carrizo aquifer is most and least favorable for future development.

Results of Aquifer Simulation

The simulation studies of the Carrizo aquifer indicate that, if pumpage remains unregulated and occurs at predicted rates, water levels will continue to decline rapidly in the heavily irrigated areas near Batesville and east of Carrizo Springs and Crystall City in Dimmit and Zavala Counties; elsewhere, water levels will slowly decline throughout the Winter Garden Area, including the downdip areas of interface between slightly saline and moderately saline ground water. The predicted water-level changes for the periods 1970-l 980, 1970-l990, and 1970-2020 are presented in the form of contour maps in Figures 21, 22, and 23.

The simulations of lines of pumping wells in areas of water-table and artesian conditions indicate that a firm water supply of 20,000 to 40,000 acre-feet (18 to 36 mgd) can be developed from the Carrizo aquifer in Wilson County for municipal use in the San Antonio region. The lines of pumping wells and their associated cones of water-level depression for the period 1970-2020 are illustrated in Figures 24 and 25. The maximum water-level drawdowns obtained from the simulations are summarized in the following table:

LINE OF PUMPING WELLS	PUMPAGE, 1970-2020 (ACRE-FEET)	MAXIMUM DRAWDOWN, 1970-2020 (FEET)
Line A	20,000 (18 mgd)	80
Line B	20,000 (18 mgd)	100
Line A	30,000 (27 mgd)	100
Line B	30,000 (27 mgd)	120
Line A	40,000 (36 mgd)	160
Line B	40,000 (36 mgd)	160

The annual recharge to the Carrizo aquifer in the area southeast of San Antonio is estimated to be approximately 26,000 acre-feet (23 mgd). The recharge area, for the most part includes the Carrizo Sand outcrop in Wilson County and parts of Atascosa, Bexar, and Guadalupe Counties. Recharge to the Carrizo aquifer would be increased as water levels are drawn down in the outcrop by the proposed well fields. The drawdown of water levels would reduce evapotranspiration losses and spring discharge into the San Antonio River and Cibolo Creek. The amount of increase in recharge which would result from the lowering of water levels in the vicinity of the outcrop was not estimated or used in the simulation studies.

Figure 26 illustrates pumpage patterns for optimizing development of ground water in the Carrizo aquifer in the Winter Garden Area. This rnap is a product of the 50-year aquifer simulation to determine the maximum constant pumping rates per unit area for the period 1970-2020, which would not bring water levels more than 400 feet below land surface or below the top of the aquifer. Possible water-quality changes due to the additional development of ground water were not considered in the analysis.

The aquifer simulation indicates that, under the constraints mentioned, approximately 330,000 acre-feet of water per year (294 mgd) could be pumped during the period 1970 to 2020 from the Carrizo aquifer in the Winter Garden Area. This is an increase of about 58,000 acre-feet per year (52 mgd) over the average annual withdrawals by large-capacity wells for the period 1963- 1969.

As shown in Figure 26, the areas favorable for future development of ground water from the Carrizo aquifer are generally located in (a) the Floresville, Stockdale, and Nixon areas of Wilson and Gonzales Counties; (b) northeast La Salle County; (c) an area west of Pearsall in Frio and Zavala Counties; (d) central and western Zavala County; and (e) central and southwestern Dimmit and northwestern Webb Counties. In these areas, approximately 118,000 acre-feet per year (105 mgd) could be developed in addition to the 1963-1969 average withdrawal rate without bringing water levels more than

400 feet below land surface or below the top of the water-bearing sands until the year 2020. The average annual withdrawal for the period 1963-1969 in these areas was approximately 22,500 acre-feet (20 mgd). The best locations for additional development generally correspond with the areas where the thickest accumulations of water-bearing sand occur within the aquifer (Figure 12j. Also, additional development must be distributed widely in order to avoid concentrated withdrawals of ground water in small areas.

Within the extensive area that is fully developed (Figure 26), ground-water withdrawal ideally should not be increased over the 1963-1969 rate, which was approximately 133,000 acre-feet per year (119 mgd).

The areas least favorable for future ground-water development from the Carrizo aquifer are the overdeveloped areas, shown in Figure 26 to be located: (a) in the outcrop of the Carrizo Sand in northern Frio, northern Atascosa, and southeastern Medina Counties; (b) at and southeast of Pearsall in Frio County; (c) near Batesville and in the outcrop of the Carrizo in northeastern Zavala County; (d) northeast, east, and southeast of Crystal City in Zavala and Dimmit Counties; and (e) near Carrizo Springs in Dimmit County. The 1963-1969 average annual withdrawal in these areas, approximately 117,000 acre-feet (104 mgd), should be reduced by approximately 59,800 acre-feet (53 mgd) if excessive water-level declines are to be avoided.

Artificial Recharge

Artificial recharge occurs when natural recharge is augmented so as to increase the amount of water entering the aquifer. The means of artificial recharge may include increasing the rate of infiltration through the soil profile, increasing the area in which surface runoff is in contact with the aquifer outcrop, and increasing the time during which the surface water is in contact with the aquifer outcrop. In addition to modifications to increase recharge in the aquifer’s outcrop, water can be injected into the aquifer in downdip areas through injection wells.

Barnes (1956) estimated that a permanent water supply of 112,000 acre-feet per year (100 mgd) could be developed from the Carrizo aquifer in Wilson County for the San Antonio region by lowering water levels in the Carrizo outcrop in Atascosa, Bexar, and Wilson Counties, which would increase the amount of direct streambed infiltration from the San Antonio River and Cibolo Creek, and by spreading other waters over the outcrop. Barnes assumes that most of the water brought in for artificial recharge would be surplus water generated by the city of San Antonio. In order to lower the water table in the outcrop, Barnes proposes drilling 18 wells along a line parallel with the lower Carrizo outcrop edge. These wells would be spaced one mile apart and each produce 1,000 gpm (gallons per minute).

When evapotranspiration losses and spring flows have ceased in the aquifer outcrop due to water-level declines, other steps to increase the amount of recharge in the outcrop appear feasible. The Winter Garden District (Dimmit, Zavala, and eastern Maverick Counties) offers excellent possibilities, as large water-level declines have taken place in the outcrop in this region. Similarly, the well field proposed by Barnes (1956) or the well fields studied in this report in Wilson County would offer excellent possibilities for artificial recharge by creating large water-level declines in the outcrop.

Artificial recharge to the Carrizo aquifer in the outcrop could be achieved by: (a) constructing a series of diked basins, superimposed on the natural stream drainage to retard runoff and promote infiltration; (b) scarifying, leveling, and widening the beds of intermittent streams to increase infiltration; and (c) transporting to the outcrop the surplus water of cities, industry, or flood runoff.

Getzendaner (1953) describes an injection well experiment on the Byrd Ranch near Crystal City. Initially the injection rate was estimated at 1,800 gpm for 38 minutes, at which time the Carrizo aquifer ceased to take water at this rate and the injection rate was reduced to approximately 900 gpm. This lower injection rate was continued for 4 hours and 45 minutes until the experiment was terminated because of darkness. Getzendaner wrote:

> Many experiments with such wells, in California and elsewhere, have had little success. But excepting in Brooklyn and Queens, Long Island, where water is injected into gravel, there has been no attempt, so far as the literature discloses, to inject water through wells into as porous and permeable, nor as thick a formation as the Carrizo Sand in this district.

Clogging of the aquifer and low injection rates are problems which must be overcome if injection wells are to function successfully. Some of the causes of clogging are algea, silt, and entrained air. Poor recharge well design and completion of recharge wells in zones of low permeability in the aquifer may also contribute to low injection rates.

The amount and cost of water which can be recharged into the Carrizo aquifer depend on the availability of recharge water, methods used, frequency of use, maintenance (clogging, weeds, sedimentation or flocculation, etc.) land costs, and capital works investment. The cost of artificial recharge projects may be reduced in part through the operation of sand pits or possibly by joint use of a recreation area. For example, sand excavated from the artificial recharge puts could be sold for construction purposes; and municipal recreational facilities such as parks, golf courses, baseball diamonds, football fields, public hunting and fishing areas, and skeet and trap ranges could be incorporated into an artificial recharge project.

Ground-Water Development Problems

Problems associated with the development of ground water from the Carrizo aquifer can be related to (a) improper well completion, (b) water-level declines, and (c) contamination of native ground water.

Improper well completion can usually be attributed to insufficient casing, open-hole rather than screened completion, slotted or perforated casing as a substitute for screen, improper gravelpacking, or lack of cement in the annulus between the casing and the borehole. The following are recommendations for the proper construction and completion of high-capacity wells in sand and gravel aquifers: (a) wells should be drilled to the base of the zone containing desirable quality water, thereby utilizing maximum saturated thickness; (b) all wells should be cased (including screen) from ground level to total depth; (c) gravel packing, when used, should be preceded by a sieve analysis of the aquifer to determine the proper size of the pack material to be used; and (d) the well should be completed with a properly designed well screen.

Large, concentrated withdrawals of ground water from storage in the Carrizo aquifer have caused large-scale water-level declines and possible contamination problems in the Winter Garden District (Dimmit, Zavala, and eastern Maverick Counties) where the aquifer has comparatively low transmissibility. This district is famous for its production of garden vegetables and has experienced a large amount of irrigation development since the late 1930’s. As a result of these large water-level declines, well yields have decreased. In order to meet increased water demands, well pumps must be set deeper and larger motors installed. In some cases, new wells are needed to meet the demands for water supplies. These improvements cause operating costs to spiral upward as ground-water users attempt to meet demands and, in doing so, cause additional water-level declines.

Prior to large-scale development of ground water in Dimmit and Zavala Counties, the hydrostatic head of the Carrizo aquifer was considerably higher than the hydrostatic head of the highly mineralized waters of the overlying sands. As the hydrostatic head of the Carrizo dropped with development in Dimmit and Zavala Counties, the mineralized waters from these sands began moving into the Carrizo as leakage through the confining beds or down the well bores in which the casing was defective, improperly installed, or had not been cemented. This water mingles with the native Carrizo water, thus deteriorating its chemical quality. Although the problem is confined to individual wells at present, continued increase in development of the Carrizo in Dimmit and Zavala Counties could result in more wide spread aquifer contamination due to interformational leakage.

Developing and utilizing ground water from a well or well field require adequate planning. Future development of ground water in the Winter Garden Area should be based on a program of test drilling, test pumping, and chemical analysis of water from the producing aquifer. Such preliminary data can be used to determine the most efficient well completion, optimum pumping rate, efficient pump setting, optimum well spacing, and feasibility of drilling additional wells. Large, concentrated withdrawals of ground water in small areas should be avoided.

GROUND-WATER AVAILABILITY IN THE WILCOX, QUEEN CITY-BIGFORD, AND SPARTA-LAREDO AQUIFERS

Estimates of the amount of water available from the Wilcox, Queen City-Bigford, and Sparta-Laredo aquifers are based on the transmission and storage capacities of the aquifers. The transmission capacity of an aquifer can be approximated for any proposed development scheme by using the formula

$$Q=TWI,$$

where

Q = the average quantity of water in gallons per day moving through the aquifer;

T = the average coefficient of transmissibility in gallons per day per foot of aquifer width;

W = the width of the aquifer in miles, parallel to the strike of the formation; and

I = the average hydraulic gradient in feet per mile.

The development scheme considered is based on the following conditions: (a) the effect of pumping is such that static water levels are drawn down to a maximum depth of 400 feet below land surface, but not below the top of the aquifer; (b) the line along which the static water levels are 400 feet below the land surface is located about midway between the outcrop and the downdip limit of fresh to slightly saline water in the aquifer; and (c) lowering of water levels within the outcrop does not occur. The average coefficient of transmissibility in gallons per day per foot (gpd/ft) was determined from the average net sand thickness and the estimated permeability along the line described above; and the average artesian storage coefficient was estimated by multiplying the average net saturated sand thickness, in feet, by 10^{-6} per foot, which is proper for most confined aquifers (Lohman, 1972, p. 8).

In determining the quantity of water available, (a) a total amount of water obtained from artesian storage by lowering the static water level to a depth of 400 feet below land surface was calculated, and (b) the amount of water that the aquifer will transmit annually after static water levels have been lowered to a depth of 400 feet below land surface was calculated.

The following table summarizes the coefficients used to estimate the amount of water which can be developed from the Wilcox, Queen City-Bigford, and Sparta-Laredo aquifers. Only the portions of the Wilcox and Queen City-Bigford aquifers east of the Frio River are included in this determination since it is doubtful that these aquifers will be developed to any great extent west of the river.

AQUIFER	COEFFICIENT OF TRANSMISSIBILITY (GPD/FT)	WIDTH OF AQUIFER (MILES)	HYDRAULIC GRADIENT (FT/MILE)	ARTESIAN STORAGE COEFFICIENT
Wilcox	44,000	123	33	5×10^{-4}
Queen City-Bigford	14,000	111	88	5×10^{-4}
Sparta-Laredo	5,000	197	81	1×10^{-4}

Based on the above figures, east of the Frio River 200,000 acre-feet of water per year (178 mgd) can theoretically be transmitted by the Wilcox aquifer and 153,000 acre-feet annually (136.5 mgd) by the Queen City-Bigford aquifer to pumping wells in the Winter Garden Area. Approximately 89,000 acre-feet per year (79 mgd) can be transmitted by the Sparta-Laredo aquifer. These are the computed amounts which can be pumped annually without lowering the static water levels below the top of the aquifer or more than 400 feet below land surface, providing that the aquifer recharge in the outcrop is sufficient. In the opinion of the authors, the areas of aquifer outcrop may be too small to supply these estimated transmission capacities and they should be reduced by a factor of 2 or 3 for judging the amount of water continuously available.

The amount of water available from storage was calculated to be 244,000 acre-feet in the Wilcox, 100,000 acre-feet in the Queen City-Bigford, and 40,000 acre-feet for the Sparta-Laredo, should static water levels be lowered 400 feet below land surface along a line midway between the outcrop and the downdip limit of fresh to slightly saline water in the aquifers. These amounts can be pumped from storage only once, not annually, and should not be considered in long-range planning.

SUMMARY

The Winter Garden Area consists of approximately 11,800 square miles and lies within the Guadalupe, San Antonio, Nueces, and Rio Grande basins. It includes all or part of Atascosa, Bexar, Dimmit, Frio, Gonzales, Guadalupe, Karnes, La Salle, Live Oak, McMullen, Maverick, Medina, Uvalde, Webb, Wilson, and Zavala Counties. Within the Winter Garden Area is found the Winter Garden District which includes Dimmit and Zavala Counties and the eastern part of Maverick County.

The Carrizo aquifer (Carrizo Sand) is the most continuous and permeable aquifer in the area and therefore is the most developed water-bearing formation. In local areas of the aquifer's extent, some of the sands containing fresh to slightly saline water in the Reklaw Formation, Bigford Formation, and Wilcox Group may be hydrologically connected to the Carrizo Sand. The Carrizo aquifer ranges in thickness from about 150 to 1,200 feet. The transmissibility of the Carrizo ranges from less than 1,000 gallons per day per foot in Webb County to 317,000 gallons per day per foot in Atascosa County. The average coefficient of storage in the outcrop of the Carrizo aquifer is approximately 0.20. Downdip, where the aquifer is under artesian conditions, the average coefficient of storage approximates 0.0005 or 5×10^{-4}.

Throughout the Winter Garden Area, the Carrizo aquifer yields fresh to slightly saline water which is acceptable for most irrigation, public supply, and industrial purposes. In the outcrop, the Carrizo aquifer contains hard water which is otherwise low in dissolved solids. Downdip the water is softer, has a higher temperature, and contains more dissolved solids. Carrizo aquifer water has a low to high salinity hazard for irrigation use, and the sodium (alkali) hazard is generally low to medium.

The average rate of recharge to the Carrizo aquifer in the Winter Garden Area is about 100,000 acre-feet per year or 89 mgd. In the heavily irrigated areas of Dimmit, Zavala, and Frio Counties, leakage into the Carrizo from other aquifers is occurring; an estimated 9,500 acre-feet per year (8.5 mgd) leaked into the Carrizo during the period 1963-1969. The approximate average annual pumpage from large wells (irrigation, public supply, and industrial) from the Carrizo aquifer in the Winter Garden Area during the period 1963-1969 was about 272,000 acre-feet (243 mgd); thus, about 162,500 acre-feet (145 mgd) of ground water was removed annually from storage in the aquifer. Although the water stored in the aquifer is in no danger of being depleted for many years, the increased pumping lifts caused by water-level declines will make it more costly to pump water for irrigation.

Contamination of native ground water in the Carrizo aquifer by water of higher mineral content from overlying sands is a serious problem in Dimmit and Zavala Counties. The water from these sands moves into the Carrizo as leakage through confining beds or down the well bores in which the casing is defective, improperly installed, or has not been cemented. At present the problem is confined to individual wells, but a continued increase in development of the Carrizo in Dimmit and Zavala Counties could result in more widespread contamination due to interformational leakage.

The digital computer simulation of the Carrizo aquifer for the period 1970 through 2020 indicates that: (a) water levels near Batesville and east of Carrizo Springs and Crystal City in the Winter Garden District will continue to decline rapidly; (b) elsewhere throughout the Winter Garden Area, water levels will slowly decline if pumpage remains unregulated and occurs at predicted rates; (c) a firm water supply of 20,000 to 40,000 acre-feet per year (18 to 36 mgd) of ground water from wells can be developed in Wilson County for municipal use; (d) approximately 330,000 acre-feet per year (294 mgd) of ground water can be developed from the Carrizo aquifer and not lower water levels below a 400-foot level below land surface or below the top of the water-bearing sands until the year 2020, representing an increase of 58,000 acre-feet per year (52 mgd) over the average withdrawals of 1963-1969; and (e) the areas most favorable for the development of additional ground-water supplies are in Wilson and Gonzales Counties.

Developing and utilizing ground water from a well or well field require adequate planning. Future development of ground water in the Winter Garden Area should be based on a program of test drilling, test pumping, and chemical analyses of water from the producing aquifer. Such preliminary data can be used to determine the most efficient well completion, optimum pumping rate, efficient pump setting, optimum well spacing, and feasibility of drilling additional wells. Large, concentrated withdrawals of ground water in small areas should be avoided.

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YEARS COVERED	TEXAS RAILROAD COMMISSION BULLETIN NO.
Beginning of operations to 1952	
1952 to 1954	47
1954 to 1956	-
1956 to 1958	–
1958 to 1960	60
1960 to 1962	62

YEARS COVERED	TEXAS RAILROAD COMMISSION BULLETIN NO.	YEARS COVERED	TEXAS RAILROAD COMMISSION BULLETIN NO.
1962 to 1964	64	1966 to 1968	68
1964 to 1966	66	1968 to 1970	70