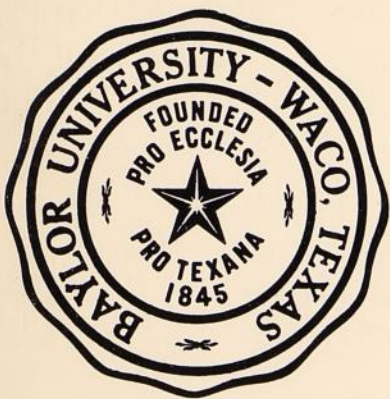


BAYLOR GEOLOGICAL STUDIES

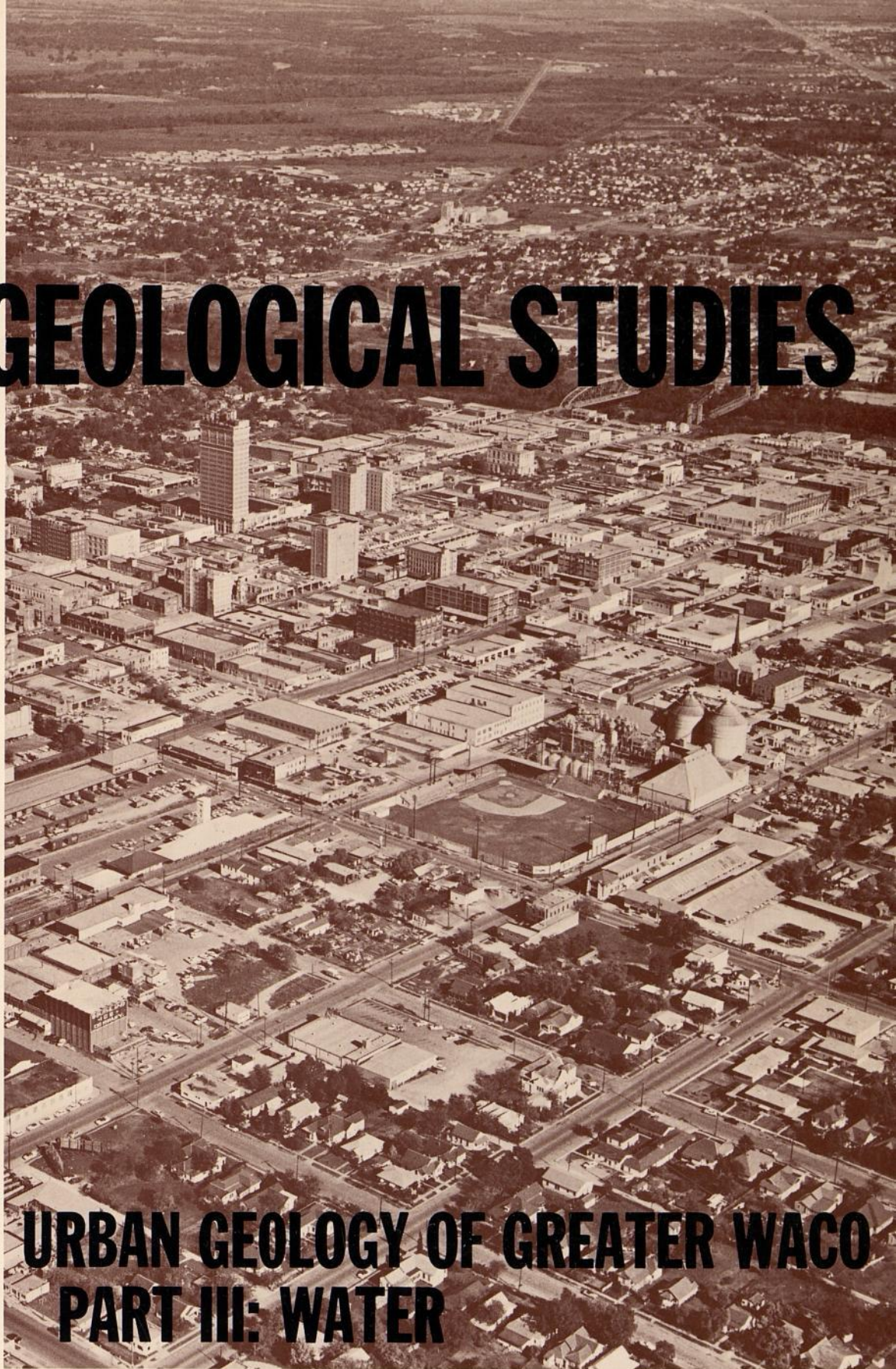
FALL 1976
Bulletin No. 11



URBAN GEOLOGY OF GREATER WACO PART III: WATER

Subsurface Waters of Waco

SIEGFRIED RUPP



*"Creative thinking is more important
than elaborate equipment--"*

FRANK CARNEY, PH.D.
PROFESSOR OF GEOLOGY
BAYLOR UNIVERSITY
1929-1934

Objectives of Geological Training at Baylor



The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

BAYLOR GEOLOGICAL STUDIES

BULLETIN NO. 11

IN COOPERATION WITH COOPER FOUNDATION

A SERIES ON

URBAN GEOLOGY OF GREATER WACO

PART III: WATER

Subsurface Waters of Waco

SIEGFRIED RUPP

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Fall, 1976

This Bulletin originally
scheduled for Fall, 1966.

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Subsurface Waters of Waco

SIEGFRIED RUPP

Geologist, Tesoro
Petroleum Corporation

ABSTRACT

Waco is situated near the eastern margin of the Trinity artesian basin and has made generous use of this water resource. The flood plains of the Brazos and Bosque Rivers, the youngest sediments in the area, also provide ground water. The Brazos alluvium is readily replenishable and can be further developed; the Bosque alluvium can produce only small amounts of ground water. Local terraces produce small and intermittent amounts of water, although they cover an appreciable area.

The primary producing units of the Trinity aquifer are the Hensel and Hosston Formations. These formations produce water of excellent quality in the Waco area and should be treated as an irreplaceable resource. To avoid polluting this aquifer and damaging the con-

ducting sands, it is imperative that the water table not be dropped beyond the capacity of this aquifer to become replenished. These formations are currently overdeveloped, primarily along the Interstate Highway 35 corridor, constituting a risk of contamination by the overlying saline Glen Rose water through improperly completed or abandoned wells or lowering of aquifer pressure.

Water from the alluvial sands does not meet U. S. Health Department standards for potable water and should be used only for irrigation. Many wells, however, are used for domestic purposes. Since this water is plentiful and readily recharged by precipitation, this water source could stand further development.

INTRODUCTION*

One of the most important resources of any area is its water supply. An aspect of water resources too often ignored is water underground. Here Waco is particularly fortunate, because, although Waco obtains its municipal water from surface sources, ground water is abundantly available to the city. The demand for ground water, and hence information concerning its availability, has grown in recent years as a result of the increased population, in turn accompanied by expansion of municipal activities, industrial output, and agricultural irrigation.

The quantity and quality of available ground water influences economy and health of the Waco area. Industrial or private waste not properly treated may pollute aquifers. Heavy pumpage from industrial or agricultural wells may lower the water table, causing adjacent wells to fail. However, most damage can be

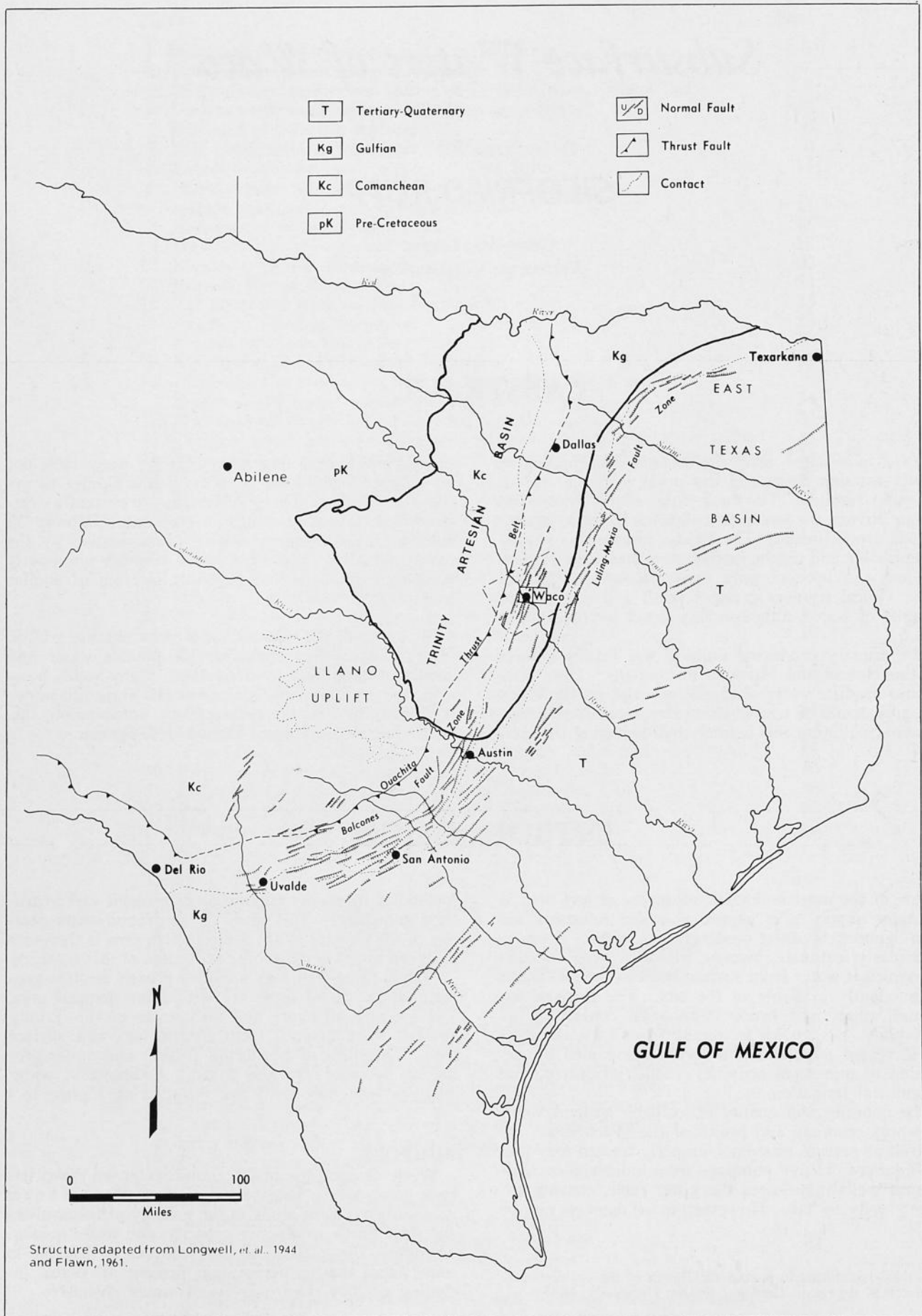
forestalled by proper application of geologic and hydrologic knowledge. This study of the ground-water geology of the Greater Waco Metropolitan area is therefore designed to aid in the proper utilization of this resource.

Ninety-three well logs provided a basis for this geologic study; 55 of these are within the mapped area. The geologic structure and thicknesses of the Trinity aquifers were mapped from electric logs and surface data. Thickness of producing section and water-producing potential are also given. Additionally, water analyses from key wells are included as Figure 18.

PURPOSE

While demand for underground water in Waco has been great over a long period of time, there is as yet no readily available study of the geology of the aquifers and their depth, productive capacity, and water quality. Therefore, the purpose of this study is to describe in some detail the aquifer system present at Waco, including geology, hydrology, and water chemistry.

*A thesis submitted in partial fulfillment of the requirements for the B.S. degree in Geology, Baylor University, 1974.



Structure adapted from Longwell, et. al., 1944 and Flawn, 1961.

Fig. 1. Index and regional geologic map, Central Texas. Dashed line encloses McLennan County. Small rectangular blocks show areas of East and West Waco topographic maps (1:24,000).

LOCATION

Waco, county seat of McLennan County, Texas, is located about 90 miles south of Dallas and about the same distance north-northwest of Austin on Interstate Highway 35. Waco is situated on the Bosque escarpment, overlooking the Brazos River at the western edge of the Gulf Coastal Plain, a portion of the former continental shelf which has been raised above sea level essentially without deformation. In Central Texas the plain consists of a wide belt of gently eastward-dipping rock layers, cut by a series of down-to-the-coast faults of the Balcones fault zone (Fig. 1). This zone is generally considered the inland boundary of the Texas Gulf Coastal Plain.

In the Waco region ground water is produced principally from the lowermost Cretaceous Trinity sand deposits of the upper Coastal Plain and from the alluvium and terraces of the Bosque and Brazos Rivers. For the current investigation the area of study includes the East and West Waco Quadrangles (Topographic maps, East and West Waco Quadrangles U. S. G. S., 1957), an area of about 100 square miles. In preparation of this report the investigation was extended into adjacent quadrangles to furnish an adequate base for subsurface control.

Because Waco lies at the easternmost margin of the Trinity artesian basin (Fig. 1), it once had numerous flowing artesian wells (Table 1). The area of recharge in Parker, Hood, Erath, Eastland, Comanche, Brown, Mills, Lampasas, and Burnet Counties (Figs. 2, 3) is updip from Waco. From the recharge area water migrates slowly downdip through the outcrop at an initial rate of feet per year; near Waco the rate slows to inches per century (Henningsen, 1962, p. 7). Downdip from the aquifer outcrop the water is under considerable static pressure which forces it upward into wells. Continued pumping has reduced the static pressure and wells no longer are free flowing. Trinity waters are potable in Waco and become more saline downdip, toward the eastern part of McLennan County.

HISTORICAL BACKGROUND

The first private water company, which depended

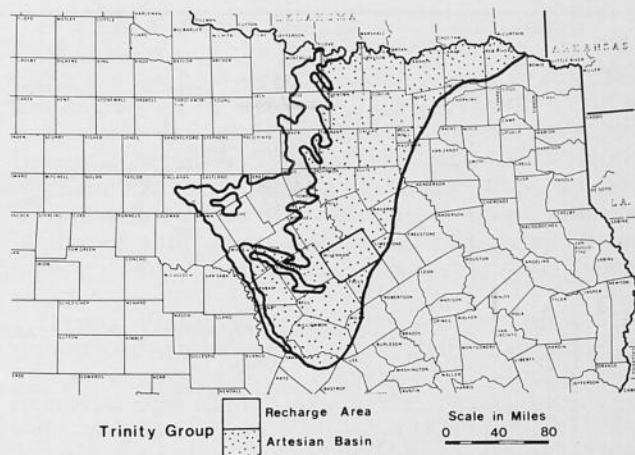


Fig. 2. Area of outcrop of Trinity aquifers (white) and extent of Trinity artesian basin (shaded). After Texas Water Development Board, Major aquifers in Texas.

largely on shallow wells, was formed early in 1872 when the population was estimated at about 2,500 persons (Davis, 1901, p. 15). On March 10, 1889, Captain J. D. Bell and Company formed a second water company with the successful drilling of a well called Jumbo #1, which encountered hot water at 1,830 feet (Conger, 1945, p. 15-26). By 1890 the population of Waco had grown to an estimated 14,445 persons (Davis, 1901, p. 15).

Early artesian wells apparently produced "cool" water from approximately 1,200 feet and hot water from approximately 1,800 feet, probably from Hensel and Hosston sands, respectively. Initial shut-in pressures at the well head in these early wells was 42 to 85 pounds per square inch and they flowed at rates of 200,000 to 1,000,000 gallons per day (Table 1). By 1894 a total of 25 wells had been drilled near Waco, 20 within the city limit (Hill, 1901, p. 540). Water temperatures averaged from 96° F to 106° F (35.5° C to 41° C). Hot artesian water was reported by *Cutter's Guide to the City of Waco* (1894, p. 1-7) to be avail-

TABLE 1. FLOWING WELLS IN THE WACO AREA, 1891

Name of well	Altitude Feet	Diameter Inches	Depth Feet	Flow / day Gallons	Temperature Degrees F.	Initial Pressure Pounds
Moore Well	493	6	1840	600,000	103	(a) 60
Bell Well (b)	500	6	1848	500,000	102½	(a) 60
Jumbo #1 (b)	500	8	1848	1,200,000	103	(c) 60
Jumbo Well #2 (b)	500	8	1860	1,000,000	103	60
Glenwood Well	495	8	1860	1,000,000	103	(a) 65
Dickey Well	532	8	1840	1,000,000	103	(a) 60
Bagby Well	475	8	1845	1,000,000	103	(a) 60
Waco Light & Power Co.	532	6	1812	300,000	100	40
Prather Well	655	6	1607	500,000	97	(c) 40
Kellum Well	420	6	1776	1,000,000	103	(c) 76
Padgett Well (Fishing Club)	485	6	1866	1,000,000	90	(c) 72
W. V. Fort Well	425	—	1825	1,300,000	—	—

Jumbo #1 and #2 belonged to the Bell Co. (a) estimated pressure; (b) these three wells, Jumbo #1 and #2, and Bell, are 50 feet equidistant; (c) tested pressure. The values given are daily flows. Jumbo #1 measurement was unsuccessful, flow estimated by U. S. Artesian Survey Corps, 1,000 gallons per minute, or 1,440,000 gallons daily. Data from R. T. Hill, 1901, p. 540.

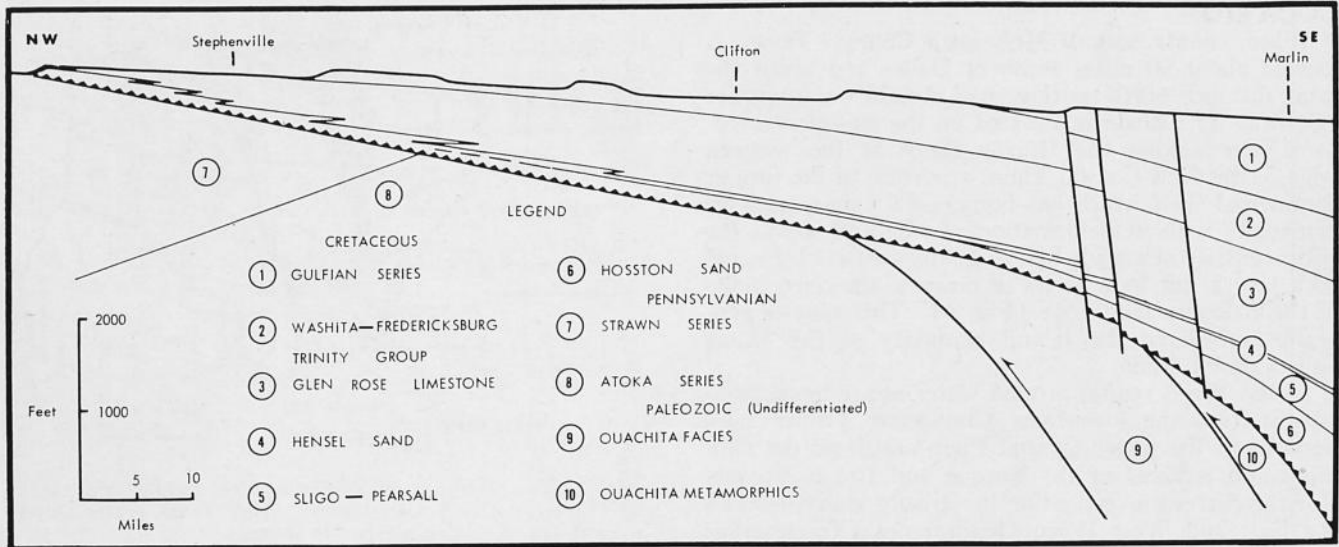


Fig. 3. Diagrammatic facies cross section of Trinity Group, Central Texas. Ouachita foldbelt data from Henningsen, 1962, p. 8.

able in "practically inexhaustible quantity—soft, clear, and sparkling." It was inferred that this asset would open a new era for the city by infusing new hope and a larger ambition into its citizens. Because of the large number of flowing wells in the area, Waco was known as "Geyser City" (Hill, 1901, p. 539). Initial flow caused wells to gush high into the air, forming an impressive spectacle (Table 1; Figs. 4, 5).

To exploit this abundant resource, numerous bath houses were erected; the most prominent were the Natatorio-Sanatorium Company and Padgett's Natatorium Park (Table 2). Miraculous cures attributed to the waters attracted tourists and health seekers (Cutter, 1894, p. 1-7).

Illustrating the attitude of the people of that time, a correspondent from Waco wrote: "So far as the his-

tory of our wells is concerned, except in the case of the well bored by Mr. Fishback and one recently drilled for Mr. Fort, of which no record was kept, all the wells around Waco have been bored by a man who has kept no record of his borings, supposedly for the reason that such records would be of value to his professional rivals" (Hill, 1901, p. 540). In a footnote, Hill (1901, p. 541) voiced regret that no detailed geological survey of McLennan County had been made at the time, since he considered it one of the most important areas in the state. Even though Hill had made a brief study to determine the sequence of formations, he felt that a more accurate and detailed study was needed to determine the thickness and extent of the producing formations, and the course of the Balcones fault zone across the county.

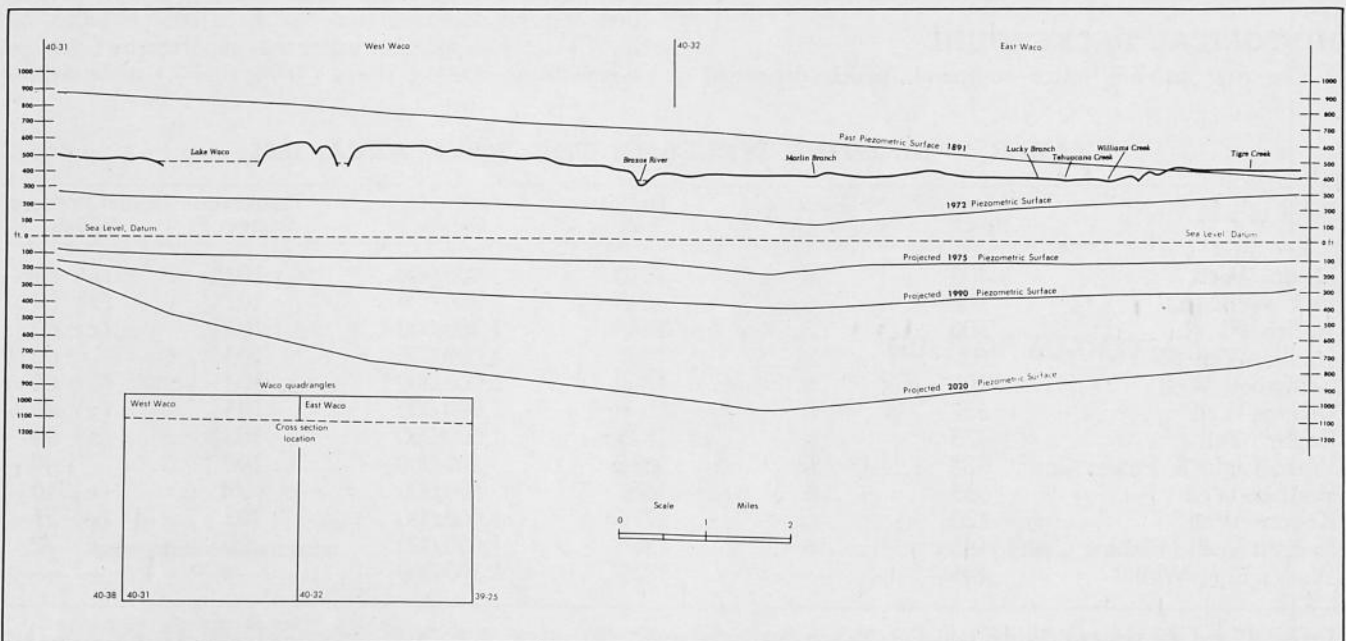


Fig. 4. West-east topographic profile showing piezometric surfaces of Trinity waters for various dates. Projected values are based on estimated production.

TABLE 2. CHEMICAL ANALYSES OF WACO WELL WATER

Natorio-Sanatorium Co. Well	
Silica	1.3456
Alumina	Trace
Iron Sesquioxide	6.0267
Sodium Chloride	1.4930
Sodium and Potassium Sulfates	23.9583
Calcium Carbonate	0.8432
Sodium Carbonate and Bicarbonate	20.6587
Calcium Sulphate	0.0000
Total Solids, by calculation in 1.000 grains	53.8201
Padgett Natatorium Park Well	
Total Residual	527.848 gr./gal.
Total Non-volatile Residue	510.062 gr./gal.
Volatile and Organic Material	17.726 gr./gal.
Chloride of Sodium	386.089 gr./gal.
Chloride of Potassium	Distinct Trace
Sulphate of Lime	13.210 gr./gal.
Sulphate of Magnesia	80.190 gr./gal.
Sulphate of Sodium	10.150 gr./gal.
Iodine	Trace
Alumina	4.480 gr./gal.
"Free" Ammonia	126.000 mg./liter
"Albumoid" Ammonia	1.000 gr./gal.
Total Ammonia	127.000 gr./gal.
Nitrates	1.000 gr./gal.

After Cutter's Guide to the City of Waco, Texas, 1894, p. 13-14.

At the turn of the century, Hill (1901) described several wells and their influence on other wells. In the town of West, a well with an initial pressure of 66 pounds promptly dropped in pressure as more wells were drilled. In Moody, where the surface is near the maximum elevation of possible flow, the first well overflowed, the second well completed caused the water level in the first well to drop 15 feet below the surface. Similar problems occurred in McGregor where early wells ceased to flow as later wells were drilled. At Waco, where the pressure was greatest because of the lower surface elevation, more than 20 wells were drilled without significantly affecting the flow of others. However, as drilling continued the enormous drain upon the reservoir caused flow from all wells to be diminished (Hill, 1901, p. 545).

The quantity of water produced by flowing artesian wells in McLennan County once ranked very high in the state of Texas. Eleven flowing wells existed in Waco in 1891. In 1897, Hill reported 27 operational and eight nonoperational wells in the county (1901, p. 545).

By 1900 the population of Waco was 20,686 (Davis, p. 15) and in 1904 the city acquired both of the private water companies. Artesian water from the Trinity wells provided most of the Waco water until 1912 when the city, now with approximately 28,500 inhabitants (Davis, p. 15), was forced to increase the supply by pumping from an infiltration gallery on the Brazos River at the present Riverside Treatment Plant (City of Waco Water Department Booklet, 1965).

In 1928, a storage reservoir was constructed on the Bosque River adjacent to Waco. While this lake provided for most city needs, production from the lake was augmented by water from deep wells, and, during particularly dry spells, water was supplied from the Brazos River. In 1965, a new and much larger reservoir was constructed on the Bosque River. In 1974 all city water comes from new Lake Waco, although infiltration galleries on the Brazos River are still maintained. Two wells are still in use to supply boiler water.

During World War II water was needed for the war-supporting industry, and a study was made by W. O. George and B. A. Barnes (1945) listing several industrial wells already in existence. Among them were wells of Waco Tap Railroad (1871) (later Waco Northwestern Railroad) and Katy Railroad. These wells may have been drilled as early as 1871 or as late as 1912. The Geysers Ice Company had a "natural" shallow well and later an artesian well (1890-1900) at the Crystal Palace Pool (the present site of the Professional Building, Fifth Street and Franklin Avenue). Other industrial wells include Buchanan Laundry (1891, second drilled in 1956), Amico Building (1909), Liberty Building (1922), Progress Laundry (1926), Texas Water Company (1942, 1945), General Tire Company (1943, 1944, 1945), Pure Milk Company (1950-1951), and Plantation Foods (1965), now used only for supplementary water or as demand indicates.

Elm Mott began use of Trinity water early in the century, and following World War II Lacy-Lakeview, Robinson, and Woodway all completed wells in the Trinity Sands. Woodway, located updip from Waco, still has eight operational wells and supplies all municipal water from wells. The other communities also depend on wells. These industrial and private wells cause a heavy drain upon the Trinity reservoir with resultant drawdown, and as a result several area wells are no longer operational.

According to the 1970 census, the population of Waco was 95,326 persons. Another 60,000 persons were reported in Bellmead, Lacy-Lakeview, Woodway, and other incorporated towns within the area of this study. Essentially all communities in this area except Waco depend upon ground water for municipal supply, and within Waco there is a large industrial demand for underground water.

PREVIOUS WORKS

The first significant subsurface report on Central Texas was written by R. T. Hill (1901). In it he discussed geology and stratigraphy giving special reference to artesian water. A water-supply study of the area by Chester B. Davis was published in the same year; however, this study lacks significant geological information. Various other reports published about the same time (Singley, 1893; Darton, 1905; and Taylor, 1907), contain records of deep wells, and the availability of water from shallow wells was briefly mentioned by Taylor.

Serious consideration was given to ground-water potential in *Results of Testing on Wells at Waco, Texas* (1945), by W. O. George and B. A. Barnes.

Later the development of ground water for irrigation of the flood plain was summarized by W. F. Hughes

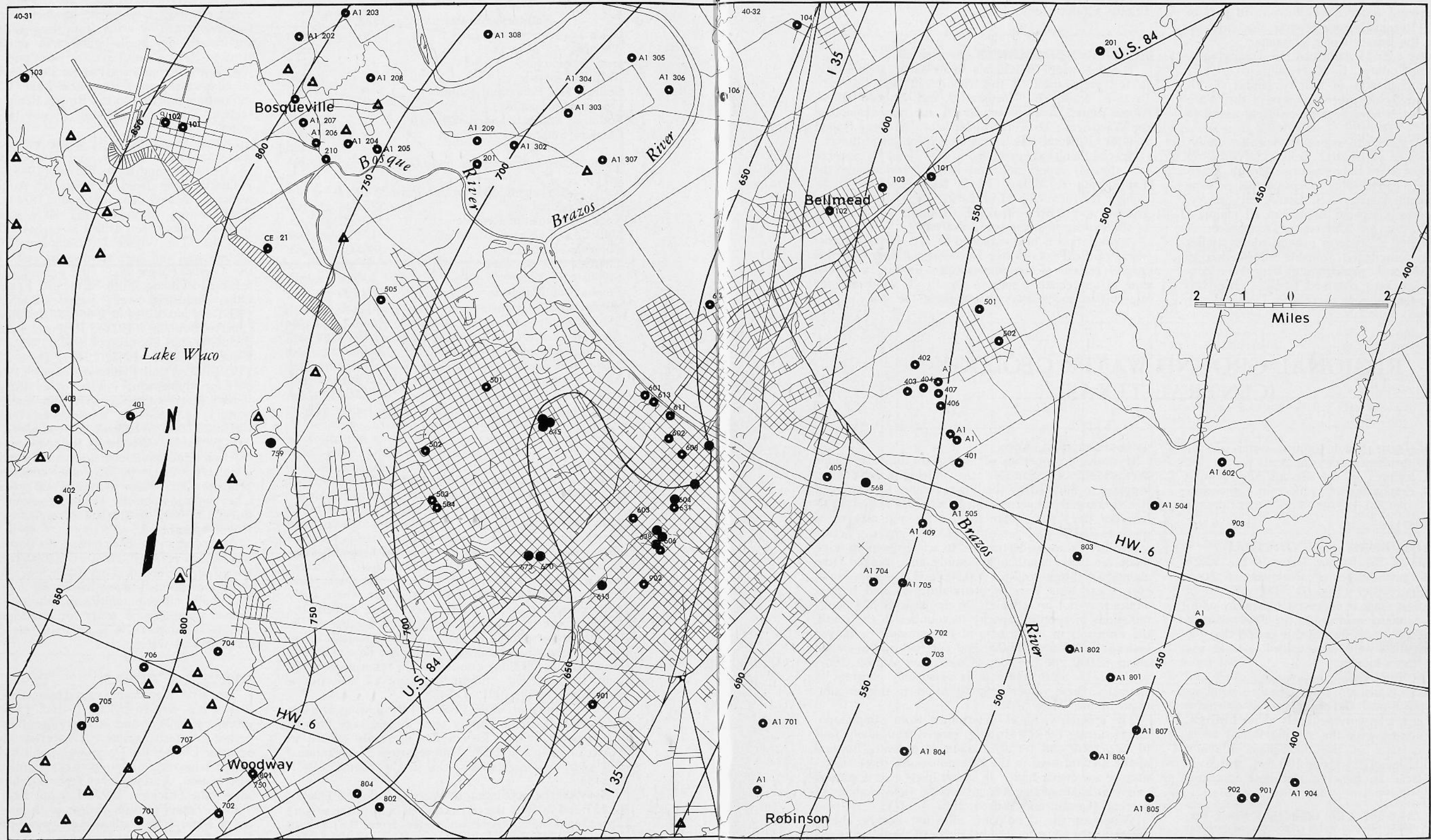


Fig. 5. Projected past piezometric surface, 1891 (undifferentiated). Other control points outside of quadrangle areas.

● Historic wells ● Well location ▲ Projected point
 ● A1 202 alluvial well ● 505 other well Contour interval 50 ft.

and A. C. McGee (1962). The U.S. Study Commission-Texas (1962, pt. 3, p. 115) also reported on the availability of ground water from alluvium in part of the Waco area. Reconnaissance reports also exist on ground water in the Brazos River alluvium.

H. D. Holloway (1961) described the Trinity aquifers of McLennan County; E. R. Henningsen (1962) considered water chemistry in Trinity sands; J. M. Burket (1965) briefly described aquifers in the Waco area. All such studies have been particularly useful to this study.

Currently, local, state, and federal agencies are studying subsurface water in Central Texas. Of those in the area, the Texas State Department of Health, Waco City Water and Engineering Departments, Texas Water Development Board, U.S. Geological Survey, and the U.S. Army Corps of Engineers all maintain open file reports. Baylor University Department of Geology has initiated short-term ground-water studies which also have contributed valuable information to this report. While basic geologic and hydrologic data for this study have been obtained from a variety of sources, those most valuable were the Texas Water

Development Board Report 41 by Cronin and Wilson and the Texas Water Development Board unpublished Trinity aquifer study.*

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The following individuals contributed significantly to the preparation of this report: Messrs. Richard Preston, Philip L. Nordstrom, and Eugene Davis, Texas Water Development Board, contributed data on the Waco area; Dr. Gustavo Morales, Dr. Jerry Namy, and Mr. Ellwood Baldwin gave helpful suggestions.

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Appreciation is also extended to Mr. Jim Bain, formerly of the Texas Water Development Board, for his careful review of the manuscript. Finally, a special note of appreciation goes to Dr. O. T. Hayward for supervision and guidance throughout the study.

REGIONAL GROUND WATER GEOLOGY (CENTRAL TEXAS)

In the Central Texas region, ground water is produced from two geological environments: (1) the flood plain and terraces of the Brazos and Bosque Rivers, and (2) deep artesian aquifers in Cretaceous rocks. Aquifer potential of the local formations is shown in Table 3.

SHALLOW AQUIFERS (UNCONFINED)

The flood plain of the Brazos River in the Waco area consists of alluvial deposits which contain large quantities of ground water (Fig. 6). The drought of the early 1950's first made it necessary to acquire additional water to maintain farming on the flood plain of the river. Therefore it was during this period that the first of many irrigation wells were drilled to make use of the water in the alluvium.

Flood-plain alluvium, consisting of clay, sand, and gravel, differs in composition from point to point as individual beds pinch out. Generally gravels or coarse sands are found at the base immediately above bedrock, though this may vary with the specific fluvial facies represented. Thickness of the flood-plain alluvium ranges from a thin veneer to about 100 feet, and averages about 45 feet. In general, thickness increases

downstream from Waco.

Hydrologic properties of flood-plain alluvium range over wide limits. Samples taken during a test-drilling program, conducted by the Texas Water Development Board, ranged in permeability from 0.001 gpd (gallons per day) per square foot in silt and clay to as much as 18,000 gpd per square foot in gravel. Transmissibility values as determined in a few pumping tests, made far to the south of the study area, ranged from about 50,000 to more than 300,000 gpd per foot. However, these tests were of short duration and highest values may not be reliable. On the basis of 351 determinations of specific capacity in counties to the south, the estimates of coefficients of transmissibility ranged between 7,300 and 208,000 gpd per foot and averaged about 42,000 gpd per foot (Cronin and Wilson, 1967, p. 25, 27). Since alluvium is reasonably constant in character, these values probably apply to thicker alluvium in the Waco area.

The specific yield, as determined from samples obtained during the test drilling, ranged from about four to 35 percent and averaged about 24 percent. Because of the method used in the determinations, these values may be somewhat high. It seems likely that a conservative estimate of the average specific yield is about 15 percent (Cronin and Wilson, 1967, p. 27).

Water in the flood-plain alluvium occurs chiefly under water-table conditions, although artesian conditions may occur locally where extensive lenses of clay are present. The top of the water table occurs at depths ranging from less than ten to almost 50 feet below the land surface, generally sloping toward the river (Fig. 7).

*Published after completion of this manuscript: Klemm, Perkins, and Alvarez, 1975, Ground-water resources of part of Central Texas with emphasis on the Antlers and Travis Peak Formations: Texas Water Development Board Report 195, vols. 1, 2. This is a remarkably comprehensive report on the Trinity artesian basin of Texas. For a clear understanding of the Cretaceous aquifers of the Waco area, readers are directed to this study, which was "mined" extensively for the current investigation.—Editor.

TABLE 3. SEQUENCE AND CLASSIFICATION OF CENTRAL TEXAS GEOLOGIC FORMATIONS

System	Series, group, or division	Formation or member	Maximum Thickness (feet)	Description	Aquifer properties	
Quaternary	Recent and Pleistocene	Alluvium and terraces	?	Sand, silt, and gravel.	Yields potable water in some areas at shallow depth.	
Cretaceous	Gulfian Series	Taylor	1170	Calcareous marls, sandy marls, lenses of calcareous sandstone, and chalky limestone.	Yields some potable water from Wolfe City member in eastern part of county at shallow depth.	
		Austin	295	Marly limestone and limy shale with some bentonite seams.	Not known to yield water in McLennan County.	
		Eagle Ford Group	South Bosque	140	Shale with limestone flags.	Yields no water in McLennan County.
			Lake Waco	145	Shale with limestone flags and bentonite seams.	Yields small amounts of water for domestic use in western part of McLennan County.
		Pepper	100	Non-calcareous shale with injected sandstone dikes in northern part of McLennan County.	Reported to yield some potable water in northeastern McLennan County.	
		Washita Division	Buda	35	Hard to chalky fossiliferous limestone.	Yields no water in McLennan County.
			Del Rio	85	Fossiliferous clay with occasional limestone beds and sandy streaks.	Yields no water in McLennan County.
			Georgetown	210	Nodular limestones and marly shales.	Not known to yield water in McLennan County.
		Fredericksburg Division	Edwards	45	Limestone, rudistid reef material, and calcareous siltstone.	Yields some potable water in northwestern McLennan County.
			Comanche Peak	130	Nodular limestones and fossiliferous clay.	Yields no water in McLennan County.
	Walnut		175	Shale with some limestone and sand stringers.	Yields no water in McLennan County.	
	Paluxy		20	Sands with some shales interbedded.	Yields potable water in northwestern McLennan County.	
	Comanchean Series	Upper	Glen Rose	800+	Alternating limestones and shales with some anhydrite.	Yields some water in McLennan County.
			Hensel	75	Fine to coarse sands with green shales.	Principal aquifer in western McLennan County. Yields large supplies for municipal, industrial, and domestic purposes.
		Middle Pearsall Formation	Cow Creek	75	Limestone and shales.	Yields no water in McLennan County.
			Hammett	100	Shale with some limestone and sand.	Yields no water in McLennan County.
			Sligo	95	Limestone and shale.	Yields no water in McLennan County.
		Lower	Hosston	800+	Fine to coarse sand with some conglomerate and varicolored shale.	Principal aquifer in eastern McLennan County. Yields large supplies for municipal and industrial purposes. Water in sands in upper part of formation in southeastern part of county may be highly mineralized.
		Jurassic	Cotton Valley Group	Schuler (?)	?	Sands and shales (?).
	Pennsylvanian (?)		?	?	Shales and metamorphics.	Yields no water in McLennan County.

After Holloway, 1961, p. 7.

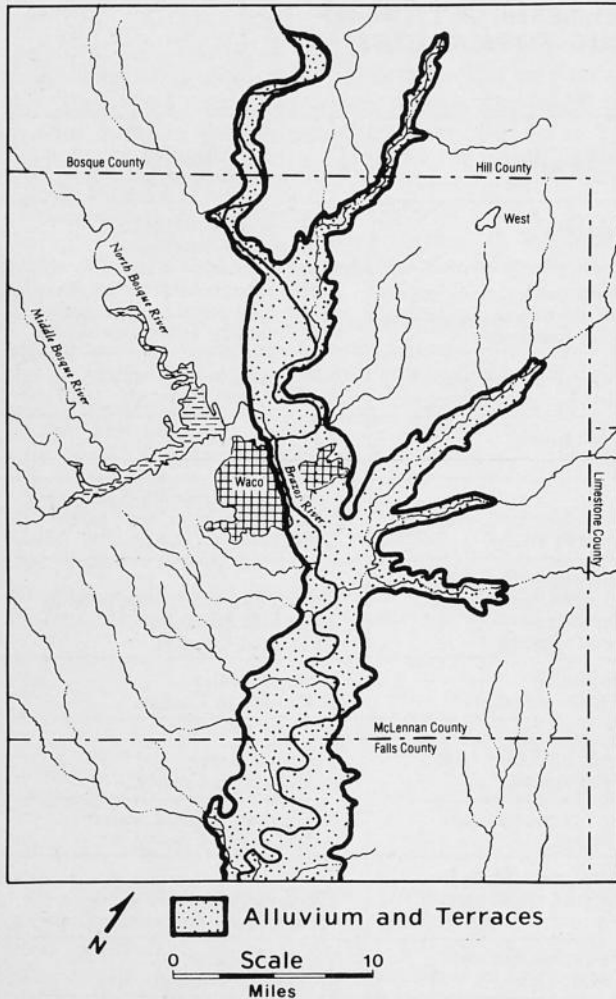


Fig. 6. Extent of alluvium and terraces, Brazos River. After Burket, 1965, p. 13.

Precipitation on the flood-plain surface is the chief recharge source to the flood-plain alluvium, although near the river bank some recharge occurs as a result of high water during floods. Various methods used to estimate recharge have given results as a rise in the water-table surface ranging from less than two inches per year to more than five inches. The average rise during the period of 1957 to 1961 is estimated to have been slightly less than 3.5 inches per year. Rainfall during this period was somewhat above normal; therefore, the estimate of recharge during this period probably represents greater than average values. In the Waco area the annual recharge during the 1957 to 1961 period was about 2,000+ acre-feet (Table 4). Additional recharge, though minor in amount, is obtained from stream infiltration, ground-water flow from terraces to alluvium, infiltration from irrigation, and, during flooding, from overbank flow (Cronin and Wilson, 1967, p. 33, 44).

Annual precipitation at Waco ranges from about 19 to more than 48 inches per year, and the alluvium of the flood plain is recharged during normal or above normal periods of rainfall (Table 4).

Ground water is discharged from the alluvium chiefly

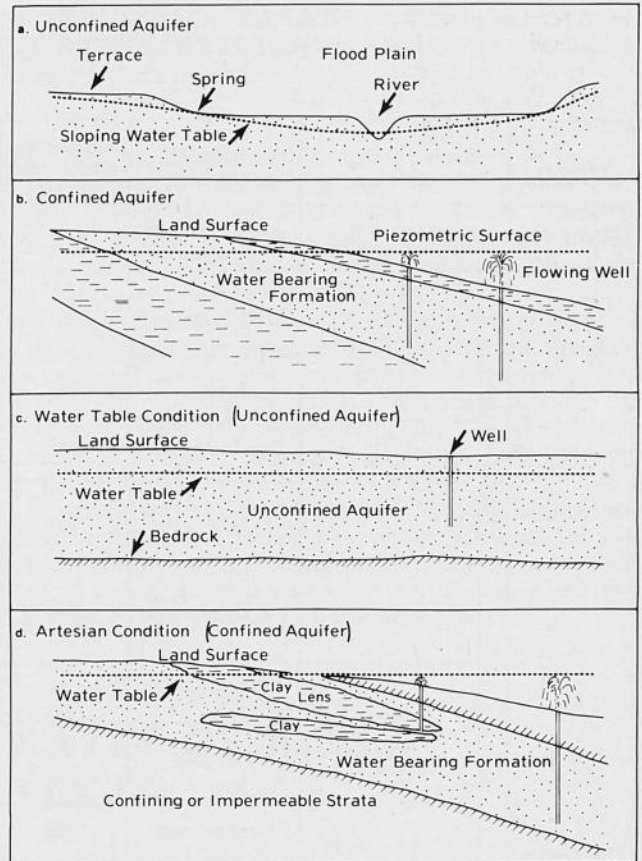


Fig. 7. Diagrammatic representation of flood plain, piezometric surface, water table and artesian conditions.

by seepage into rivers, evaporation and transpiration, and pumping wells.

TABLE 4. ANNUAL PRECIPITATION AND DEPARTURE FROM NORMAL PRECIPITATION IN INCHES, AT WACO, 1957-1964

Year	Precipitation	Departure from normal
1957	48.91	15.96
1958	35.31	2.36
1959	33.81	0.86
1960	29.63	-3.42
1961	42.71	9.76
1962	22.60	-9.48
1963	19.57	-12.51
1964	29.32	-2.76

From records of U.S. Weather Bureau; adapted from Cronin and Wilson, 1967, p. 43.

Most of the wells in the flood-plain alluvium are used for irrigation. In 1964 more than 1,200 irrigation wells were available for use in the Brazos River flood plain from Lake Whitney to the Gulf Coast; about 150 of these were in the Waco area. Most wells are 14 to

18 inches in diameter. The casing is generally slotted and most of the wells are gravel packed. Irrigation wells range in yield from less than 250 to more than 1,000 gpm (gallons per minute). About 50 percent of the wells yield between 250 to 500 gpm (Cronin and Wilson, 1967, p. 47).

During 1963 and 1964 about 150 acre-feet of water were produced to irrigate more than 217 acres of farm land in the Waco area. Other uses of ground water on the flood plain are considered hydrologically insignificant (Cronin and Wilson, 1967, p. 51).

The chemical quality of the water produced from the flood-plain alluvium is variable. Generally, the water is suitable for domestic and livestock purposes, although some wells produce hard or very hard water, often polluted. Most of the water is rated as low-sodium hazard and high-salinity hazard for irrigation (U.S. Salinity Laboratory Staff classification). However, with the conditions of irrigation and climate present in the report area, the water appears to be marginally suitable for irrigation.

Alluvium exists in both terraces and flood plain (Fig. 6). While terraces generally adjoin the flood plain, in other places they are separated from the flood plain by exposures of bedrock. Terrace material consists of clay, silt, sand, and gravel, some of which is slightly cemented. Terrace deposits may be as much as 75 feet thick; however, the average is considerably less. Only small amounts of water can be found in the terraces, and it is available mainly in the rainy seasons and serves for limited domestic use.

DEEP AQUIFERS, (CONFINED)

McLennan County (Fig. 1) is situated near the western boundary of the Gulf Coastal Plain of Texas. Geologic formations exposed in the county (Table 3) are of Quaternary and Cretaceous age. Rocks of the Gulf Series (Upper Cretaceous) are exposed in the

eastern part of the county. Rocks of the Comanche Series (Lower Cretaceous) are exposed in the western part.

The dip of Cretaceous strata in McLennan County varies from 30 feet per mile in the west to about 90 feet per mile in the east (Fig. 8). Individual beds thicken toward the East Texas basin. The Cretaceous section thickens from 1,075 feet near the western margin of McLennan County (Falcon #1 Mattlage) to about 3,840 feet in the east. This west-to-east thickening of Cretaceous rocks is caused by thickening of practically all units (Fig. 3). Cretaceous sediments rest unconformably on the Paleozoic "Ouachita Facies" throughout much of the county, except in the extreme southeastern corner where they may be underlain by truncated beds of Jurassic Age (Holloway, 1961, p. 8). The lowermost Cretaceous beds comprise the Trinity Group.

The Trinity Group consists of two distinctive rock types, a lower section dominated by sands and an upper section dominated by limestone (Adkins, 1923, p. 23). The principal water-producing sands of the Trinity Group occur in the lower, sandy section; these include the lowermost Cretaceous sand, the Hosston, and in sequence above it finer, less widely distributed thinner units called the Pearsall Formation and the Hensel sand. In the western part of the county the principal water producer is the Hensel sand, primarily because it occurs at shallower depths, and therefore drilling costs are less and the demands for water are more limited. In the eastern part of the county, because of the thinning of the Hensel sand, the Hosston sand is the principal producer. In the city of Waco the Hosston is the principal water producer.

Water in the Trinity sands originates as rainfall at the outcrop area (Fig. 2). This area presently receives approximately 30 inches of rainfall annually (Henningesen, 1962, p. 9), a small fraction of which enters the aquifers as recharge. Surface water seepage from lakes

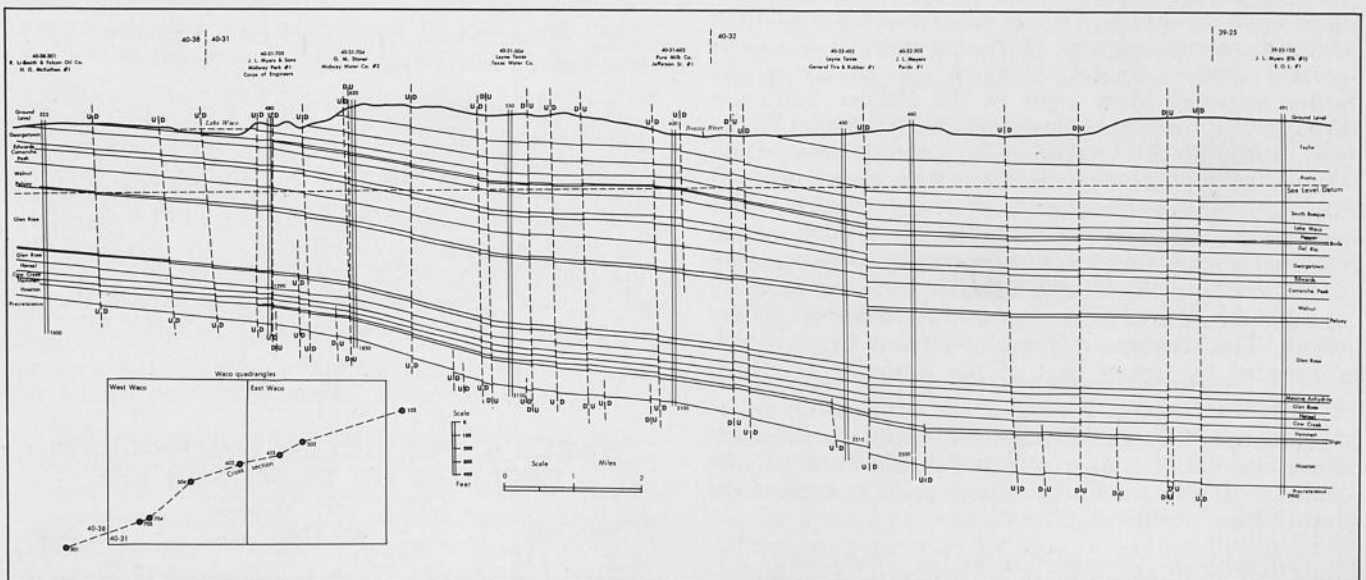


Fig. 8. West-east structural section, showing structural dip and probable faults, Waco area.

and streams, on the outcrop, is also a source of ground water to the Trinity Sands. Presently recharge is also occurring due to irrigation on the outcrop; however, this seepage is recent and has no effect on the water supply at Waco.

Regionally, ground water in the Hensel and Hosston Formations of the Trinity Group occurs under both water-table and artesian conditions (Fig. 7). The lower sands of the Trinity Group are geologically and hydraulically continuous. Both formations have a common piezometric surface and the same quality of water. In general the piezometric surface displays about the same slope as the regional topography (Henningsen, 1962, p. 9).

In the outcrop area, sands and gravels of the Trinity Group are not water saturated, and water-table conditions prevail (Fig. 7). Ground water present in one area of the outcrop may be absent in another due to localized sand and shale facies as well as channel-like sand bodies characteristic of the Trinity Group. In addition, sand lenses interbedded with shales within the members of the Trinity Group create localized perched water tables and minor artesian conditions in the outcrop area.

Downdip, artesian conditions exist because aquifers are overlain by impermeable beds (Fig. 7). Aquifers are completely water saturated and the hydrostatic pressure is great enough to cause static water levels to rise above the aquifer boundaries and, in some cases, to cause wells to flow. In the recent past, the piezometric surface was above ground level at lower elevations downdip from the outcrop area (Fig. 7), and flowing wells existed. More recently overdevelopment has caused water levels (potentiometric surface) to decline in some areas more than 750 feet below the land surface, where flowing wells had previously existed. Most of these wells are supplied from the Hosston Formation.

While Paluxy Sand (Table 3) produces water northwest of Waco, it pinches out in the Waco area and thus yields no water. Paluxy Sand reaches maximum thickness north and west of Waco, where it is an important shallow aquifer, although the quality of the water is poor. Most wells in the Paluxy Sand are artesian and some were flowing as late as 1961 (Holloway, 1961, p. 12). Additionally, several wells within the county produce from the Glen Rose Limestone, but the water is highly mineralized and is therefore not suitable for domestic use. Because of the high sulfate content of the Glen Rose Limestone, wells passing through it into the Trinity aquifers must be properly cased and cemented to prevent contamination of Trinity water. The Meadows #1 Smith well near Erath, which penetrated the upper part of the formation, contains potable water.

Although mineralized water is present in the Glen Rose Formation, and its potential should eventually be considered, here no effort has been made to explore the possibilities of this aquifer.

The increase in population in the Waco area, primarily along the route of Interstate Highway 35, has created a steady increase and demand for potable water.

Baldwin (1972, p. 109) reports that approximately 16,816 acre-feet of ground water were produced from the Trinity aquifers in 1967 in the Waco area.

Waco is the third largest consumer of ground water in the Central Texas area, although today only two wells are still being used by the city. In 1970 these two wells produced 604 acre-feet of ground water.

TABLE 5. GROUND WATER FROM TRINITY AQUIFERS, HENSEL and HOSSTON

City	No. of Wells	Acre-feet produced			
		1967	1968	1969	1970
Waco	35*	582	531	633	604

*Only two active in 1972. From TWDB unpub. Trinity aquifer study.

In the Waco area approximately 3,659 acre-feet of ground water were extracted from the Trinity aquifers in 1967 for industrial purposes. Pumping of industrial wells has remained fairly constant (Baldwin, 1972, p. 112). The largest single user of artesian water in Central Texas, although not in the immediate Waco area, is Rocketdyne Division of North American Rockwell in McGregor. From five wells completed in the Hensel sand it pumped about 680 acre-feet of water in 1967. All of these wells are located updip from Waco.

The second largest consumer of industrial ground water in the Waco area is General Tire and Rubber Company located in East Waco. In 1967, 630+ acre-feet of water were used. These two wells are completed in the Hosston Formation (TWDB open file).

Other industrial wells in the Central Texas area which produce large amounts of ground water are: Universal Atlas Cement Company, 153 acre-feet; Plantation Foods Inc., 147 acre-feet; Taylor Bedding Manufacturing Company, 129 acre-feet; Pure Milk Company, 80 acre-feet; and Buchanan Laundry, 120+ acre-feet (TWDB open file).

A computer simulation of the Trinity aquifers, projected to the year 2020 (Table 6) indicates water-level declines of magnitudes of 1,000 feet in areas of heavy ground-water use (TWDB open file). This means that lifting of as much as 1,600 feet will be necessary for some Waco wells. In addition to the increased lifting cost is the probable marked decline in the quality of the water being mined, the result of induced mixing with overlying Glen Rose water (Baldwin, 1972, p. 113).

TABLE 6. PREDICTED WATER-LEVEL DECLINES (IN FEET) FOR THE CITY OF WACO

1967-1975		1967-1990		1967-2020	
250	114	250	312	250	770

Adapted from TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 18.

GROUND WATER OF THE WACO REGION

GEOLOGY

SHALLOW AQUIFERS

The shallow aquifers in the Waco area consist of the alluvium and terraces of the Quaternary system. The largest of these systems is the alluvium which comprises approximately 25 square miles or about one-fifth of the two-quadrangle study area.

Alluvium

The flood plains of the Brazos and Bosque Rivers are the youngest sediments in the area. Presently the Brazos River flood plain (the larger of the two) is undergoing fine-grained alluviation as a result of the many dams along its course which trap the coarser sediments (Epps, 1973, p. 5; Bronaugh, 1950, p. 2).

Distribution. In the northern part of the Waco area, where the Brazos River crosses the Austin Chalk, the alluvial belt is narrow. In the southeastern part of the Waco area, where the Brazos River crosses the less resistant Taylor Marl, the alluvial belt widens considerably. In the easternmost part of the Waco area lateral migration of the Brazos River channel, which recharges the flood plain periodically, leaves alluvial deposits in a two-mile-wide belt (Burket, 1965, p. 19). Sand and gravel of the alluvial bottoms provide an excellent source of ground water for limited agricultural or domestic use.

The alluvial deposits of the Bosque River are much more limited than those of the Brazos River and are exposed in a narrow belt below the Lake Waco Dam (Figs. 6, 9). Most of the Bosque River alluvial deposits are derived from the dominantly limestone and clay of outcropping Lower Cretaceous rocks. Some Bosque River sediments, however, are derived by erosion of silicious sand and gravel of older and higher terraces of the Brazos River (Burket, 1965, p. 20).

Water. The highly permeable sand and gravel of the Brazos alluvium produce large quantities of ground water suitable for agricultural and domestic use. This shallow ground water is recharged by normal seepage from the Brazos River and rainfall on the flood plain. Potential for contamination is high, rendering some ground water unsuitable for drinking water without extensive treatment. Agricultural fertilizers are widely used in this flood plain and pose a threat to any well located in the alluvial deposits. Economical treatment of such water is impractical but nonetheless it is used by a large number of families along this flood plain.

The sand and gravel of the Bosque alluvium produce a small quantity of ground water suitable for limited agricultural and domestic use. This shallow ground water is recharged by normal seepage from Lake Waco and by rainfall. Water in this aquifer is often polluted by septic sewage effluent or by agricultural fertilizers. Although the Bosque alluvial sediments are generally less permeable than those of the Brazos alluvium, they

transmit fluids in considerable quantity, primarily in rainy seasons (Burket, 1965, p. 20).

Other limited areas of alluvial deposits (Fig. 9) occur within Waco along Waco Creek, Cottonwood Creek, Lucky Branch, Tehuacana Creek, Williams Creek, and Tradinghouse Creek, though these are not known to be exploited for ground water.

Ground water taken from the alluvial sand and gravel of the Brazos River flood plain in the Waco area is used almost exclusively for irrigation. Little or no water was used for this purpose prior to the 1950's and the number of irrigation wells in existence in this area was limited. By 1963 the use of flood-plain irrigation water along the Brazos River had increased to an estimated 150 acre-feet per year (Cronin and Wilson, 1967, p. 51).

Flooding recharges alluvial aquifers. Since much of the flood plain is agricultural land, periodic flooding is an effective recharge mechanism where recharge is most needed. Irrigation, based on flood-plain alluvial wells started in the late 1940's, has increased year by year until the present time. Row crops, principally cotton, are the dominant flood-plain produce, though smaller areas are yet in grass and woodland. Sand and gravel operations, though conspicuous, occupy only a small portion of the Brazos flood plain, except in the area nearest Waco (Cronin and Wilson, 1967, p. 10).

Brazos River alluvium, consisting of siliceous gravel, sand, silt, and clay, was deposited by the Brazos River as channel, bar, and overbank deposits (Epps, 1973, p. 5).

Deposits tend to grade from coarse at the base, where alluvium is in contact with bedrock, to finest at the surface, where overbank deposits mantle the flood plain. However, locally there may be sections which consist almost entirely of gravel, or of sand or clay.

Alluvium ranges from a thin veneer to more than 50 feet thick, though it averages 30 to 45 feet (Tables 7, 8). Brazos River alluvial gravels are typically siliceous, consisting largely of varicolored quartzite, chert, and quartz. Adjacent to limestone bedrock, limestone becomes a significant component of the gravel, though downstream from the source it rapidly decreases in relative abundance (Cronin and Wilson, 1967, p. 21).

Terraces

Terraces of the Waco area are remnants of older river flood plains of Quaternary age left as "steps" by more recent down cutting (Burket, 1959, p. 20). In the Waco region there are two well defined terrace systems, the Bosque and the Brazos systems. Remnants of terraces from 20 to 25 feet above present level of the river illustrate the levels of earlier Brazos River alluviation. Remnants of terraces ten to 40 feet above present level of the Bosque River mouth represent earlier deposits (Burket, 1959, p. 20).



Fig. 9. Surface geologic map showing extent of terrace and flood-plain alluvium. Terrace and alluvial wells are indicated by solid dots.

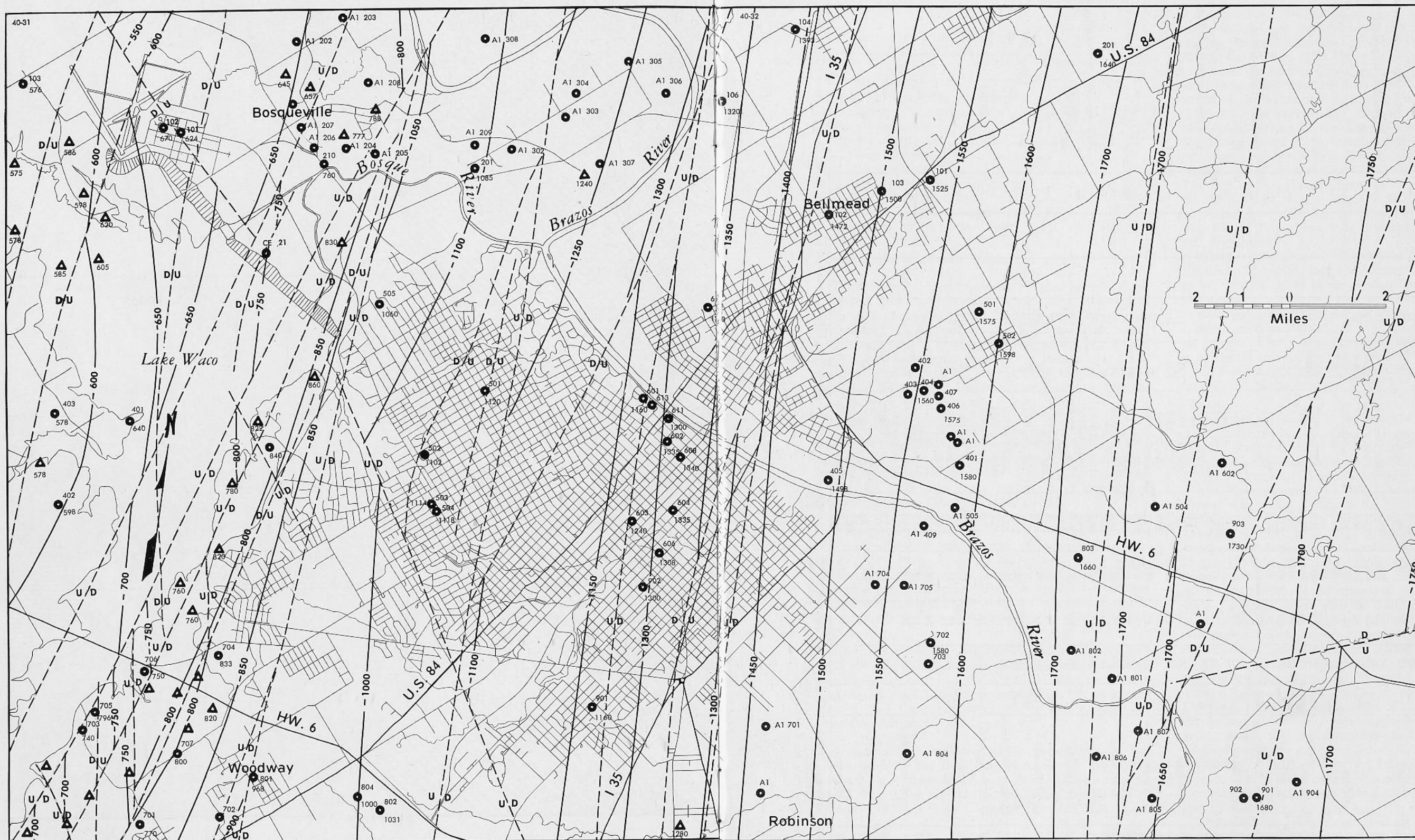


Fig. 10. Geologic structure on top of Hensel Formation.

502 Well Structural contours (based on Top of Georgetown) D = Downthrown ● Well location ▲ Projected point
 1102 Depth of formation (Sea level Datum) - - - Fault U = Uprthrown ● A1 202 alluvial well ● 505 other well Contour interval 50 ft.

TABLE 7. RECORDS OF WELLS, SPRINGS, AND TEST HOLES, BRAZOS RIVER VALLEY, WACO AREA

Well	Owner	Date completed	Depth of well (ft.)	Diameter of well (in.)	Altitude of land surface (ft.)	Water level		Method of lift	Use of water	Well performance data		Remarks
						Below land surface datum (ft.)	Date of measurement			Discharge (gpm)	Draw-down (ft.)	
ST-40-31-202	— Washington	—	25	36	456	22.9	Dec. 18, 1962	-E	D	—	—	Well taps older terrace alluvium.
203	— Griffin	—	19	27	437	14.6	do	-E	D	—	—	Do.
204	— Melton	—	26	30	441	22.8	do	-E	D	—	—	Do.
205	—	—	10	30	397	6.0	do	-E	D	—	—	Well taps older terrace alluvium.
206	—	—	21	30	441	17.4	Dec. 19, 1962	-E	D	—	—	Stream nearby.
207	—	—	30	32	454	26.1	do	-E	D	—	—	Well taps older terrace alluvium.
208	G. W. Taylor	1953	45	30	448	36.8	do	J,E	D	—	—	Well taps older terrace alluvium.
209	— Melton	—	20	36	423	14.2	do	J,E	D,S	—	—	Do.
302	W. Carson	—	21	32	410	16.8	do	J,E	D	—	—	Well taps older terrace alluvium.
303	D. L. Reed	—	27	100±	409	—	do	-E	D	—	—	Do.
304	—	—	20	30	409	18.5	Dec. 19, 1962	-E	D	—	—	Do.
305	— Melton	—	37	30	404	31.8	Dec. 20, 1962	-E	D,S	—	—	Well taps older terrace alluvium.
306	—	—	42	18	405	35.0	do	J,E	D,S	—	—	Do.
307	U. R. Allsup	—	33	30	400	23.9	do	J,E	D	—	—	Do.
308	Wayne Cox	—	58?	24	400	21.3	Dec. 6, 1962	-E	Irr	—	—	Well taps Trinity Group.
32-101	Casey & Newman Housing Division	—	—	—	445	—	—	—	P	—	—	*
401	Edgar Hicks	—	21	18	395	12.1	Dec. 5, 1960	N	N	—	—	Well taps older terrace alluvium.
406	do	—	23	18	403	13.7	Oct. 8, 1964	—	S,Irr	—	—	Do.
407	do	—	19	18	412	8.3	May 9, 1961	Cf,G	S,Irr	—	—	Well taps older terrace alluvium.
408	J. Buchheit	—	28	—	417	12.1	Mar. 15, 1963	T,G	Irr	—	—	Do.
409	—	—	38	18	384	21.7	Dec. 5, 1960	T,G	Irr	—	—	*
503	— Wardlaw	—	21	18	382	16.9	Oct. 8, 1964	N	N	—	—	Well taps older terrace alluvium.
504	do	—	21	18	378	13.0	do	N	N	—	—	Do.
505	— Hicks	—	19	30	392	15.7	Mar. 15, 1963	N	N	—	—	Well taps older terrace alluvium.
ST-40-32-601	— Wardlaw	—	26	18	380	14.6	Mar. 14, 1963	N	N	—	—	Do.
602	do	—	19	18	383	12.2	do	N	N	—	—	Well taps older terrace alluvium.
701	Patton & Greer	—	59	18	427	33.4	May 10, 1961	N	N	—	—	Temp. 67° F.1
703	Dave Simon	—	50	18	388	34.8	Mar. 18, 1963	T,E	Irr	—	—	Temp. 73° F.1
704	—	—	20	8±	395	16.6	Jan. 27, 1962	N	N	—	—	Well taps older terrace alluvium.
705	— Williamson	—	43	18	387	21.8	Oct. 8, 1964	J,E	D	—	—	Temp. 67° F.1
706	—	—	22	72	387	17.0	do	-E	Irr	—	—	Temp. 73° F.1
707	—	—	24	42	387	14.5	Mar. 18, 1963	-E	Irr	—	—	Temp. 73° F.1
801	Citizens Nat'l Bank	—	53	16	387	22.7	do	T,E	Irr	—	—	Temp. 73° F.1
802	Ovid Youngblood	—	47	18	380	22.5	Nov. 17, 1960	T,G	Irr	—	—	Temp. 73° F.1
804	—	—	18	72±	395	27.2	Mar. 14, 1963	T,G	Irr	—	—	Temp. 73° F.1
805	— Wind	—	44	18	381	28.6	Nov. 17, 1960	N	N	—	—	Temp. 73° F.1
806	—	—	35	18	383	13.2	Oct. 9, 1964	T,G	Irr	—	—	Temp. 73° F.1
807	—	—	44	18	381	16.4	Mar. 18, 1963	N	N	—	—	Temp. 73° F.1
901	Smith & Poage	—	27	16	381	18.0	May 25, 1964	-E	S	—	—	Temp. 73° F.1
902	do	—	27	16	381	16.6	Mar. 18, 1963	J,E	S	—	—	Temp. 73° F.1
903	— Wardlaw	—	21	18	379	25.9	Mar. 18, 1963	T,G	Irr	—	—	Temp. 73° F.1
904	— Biersen	—	15	30	380	12.4	Nov. 17, 1960	T,G	Irr	—	—	Temp. 73° F.1
						15.1	Mar. 14, 1963	H	N	—	—	Temp. 73° F.1
						17.2	Nov. 17, 1960	N	N	—	—	Temp. 73° F.1
						7.3	June 30, 1964	N	N	—	—	Temp. 73° F.1
						12.7	May 9, 1961	N	N	—	—	Temp. 73° F.1
						11.1	Mar. 14, 1963	N	N	—	—	Temp. 73° F.1

Adapted from Cronin and Wilson, 1967, p. 117-119. Method of lift: Cf, centrifugal; E, electric; G, gasoline, butane, or Diesel engine; H, hand; J, jet; N, none; T, turbine. Use of water: D, domestic; Irr, irrigation; N, none; P, public supply; S, stock.

*For water levels in wells see Table 9.

TABLE 8. SAMPLE LOG OF SELECTED TEST HOLES, BRAZOS RIVER VALLEY, WACO AREA

Well ST-40-40-515

	Thickness (feet)	Depth (feet)
Soil, sandy clay, loose, gray-brown ---	3.5	3.5
Clay, blocky, gray-black -----	9.5	13
Sand, coarse to fine grained, marly, brown -----	9	22
Clay, sandy, brown -----	2	24
Sand, coarse grained -----	1	25
Sand, with gravel (estimate gravel ½-in. diameter or less) -----	6	31
Marl, blocky, tight, brown-gray to black, weathers buff (Taylor Marl) -----	5	36

Adapted from Cronin and Wilson, 1967, p. 148.

Distribution. Four Quaternary terraces have been described, based on elevation above mean low water level: (1) the lower terrace, 20 to 50 feet above mean low water; (2) the second terrace, 50 to 75 feet above mean low water; (3) the third terrace, 75 to 125 feet above mean low water; and (4) a fourth level composed of terrace material higher than 125 feet above mean low water. This upper terrace ranges northeastward beyond the map area (Burket, 1965, Pls. I, II, and p. 21).

The porous terrace subsoil has good water-bearing capacity. Lower terraces are primarily composed of siliceous sand and gravel (quartz, chert, and quartzite) and smaller amounts of reddish clay. Near the outcrop of Austin Chalk, terraces also contain large numbers of limestone pebbles (Burket, 1965, p. 21).

Water. Brazos River terraces commonly support an extensive growth of deciduous trees. These terraces are veneered with good agricultural soils and high permeability makes them ideal for disposal of water waste. Terraces near the river store limited quantities of ground water suitable for domestic use after treatment for bacterial pollution. Because of the high permeability septic sewage may flow into nearby wells (Burket, 1965, p. 21).

Bosque River terraces in the Waco area are found west of Lake Waco and are composed mostly of clay and limestone gravel of the North, Middle, and South Bosque Rivers. Limited ground water is produced from these terraces, although quality and quantity are generally marginal.

DEEP AQUIFERS

Deep aquifers include two major sandstone beds. The Hensel sand is the first sand encountered in drilling below the basal beds of the Glen Rose Limestone (Figs. 10, 11, 12). The Hosston Formation is the lowermost formation of the Trinity Group of Central Texas (Figs. 13, 14, 15).

Hensel

Description: The Hensel sand is white sucrosic generally fine grained, subrounded to subangular, unconsolidated sand, interbedded with green shale (Holloway, 1961, p. 16). The size range of the Hensel sand on outcrop varies from 0.06 to 2.0 mm. (Boone, 1965,

p. 23), though fine-grained size predominates in the Waco area.

Distribution. In the Waco area the Hensel sand varies in thickness from 30 to 70 feet (Fig. 11). Electric logs indicate a tendency to thin in the northwestern part of the county. The Hensel sand is a good aquifer in western McLennan County as indicated by the large number of wells completed in this formation west of Waco. It is the second most important aquifer in the Central Texas region, and most of the domestic and stock wells drilled to the Trinity aquifers in western McLennan County are completed into this formation (Baldwin, 1972, p. 119). The formation decreases in thickness and becomes finer and more shaly eastward. The dip of the Hensel increases from approximately 40 feet per mile west of Waco to 133 feet per mile east of Marlin in Falls County (Baldwin, 1972, p. 120). The Hensel Formation rests conformably on the Pear-sall Formation.

Water. Numerous industrial and domestic wells have been completed into the Hensel sand. The quality of the water is good in the western part of the county, but east of the Balcones escarpment it becomes highly mineralized, apparently due to seepage from the overlying Glen Rose Formation, or from admixing of connate brine. The net producing sand (Fig. 12) varies in thickness from 30 feet in western McLennan County to 50 feet in eastern McLennan County, averaging 40 feet in the Waco area.

Hosston

Description. In the Waco area the Hosston Sand is a fine-to-coarse, red-to-white, silty porous sand and fine gravel, cemented with calcite and interbedded with variegated shale in the upper part (Holloway, 1961, p. 61). Conglomerate is encountered in the basal part of the Hosston sand in Central Texas. In the C. M. Stoner #1 Spring Valley well (Fig. 3) this conglomerate was too coarse to pass through the shale shaker (Holloway, 1958, p. 37-38). Samples from other wells contained pebbles of quartz, and chert fragments (Holloway, 1958, p. 38). The pebbles and sandy conglomerates of the Hosston Formation are generally poorly sorted, multicolored, and cemented by calcite or opaline silica. The formation consists most commonly of fine to very coarse-grained sand and sandstone, poorly to well sorted, poorly to well cemented with calcite or less commonly with opaline cement. Color ranges from gray to tan through red-brown. Sandy and silty clay with some waxy clay of gray, green, yellow or brown color, various colored shales, and occasionally thin beds of limestone occur in the formation. Crossbedding is commonly associated with the conglomeratic beds which range from thin to massively bedded. Sands and conglomerates are predominantly siliceous with pebbles consisting of chert or quartz (Baldwin, 1972, p. 117). Conglomeratic zones commonly occur at the base. They decrease in abundance and frequency toward the top of the formation.

Distribution. The thickness of the Hosston Formation varies from 100 feet west of Waco to 440 feet east-southeast of the Waco area (Fig. 14). The formation dips 40 feet per mile west of Waco increasing to about 150 feet per mile east of Waco.

Water. Of the Trinity aquifers in the Waco area the Hosston sand is by far the most productive. All

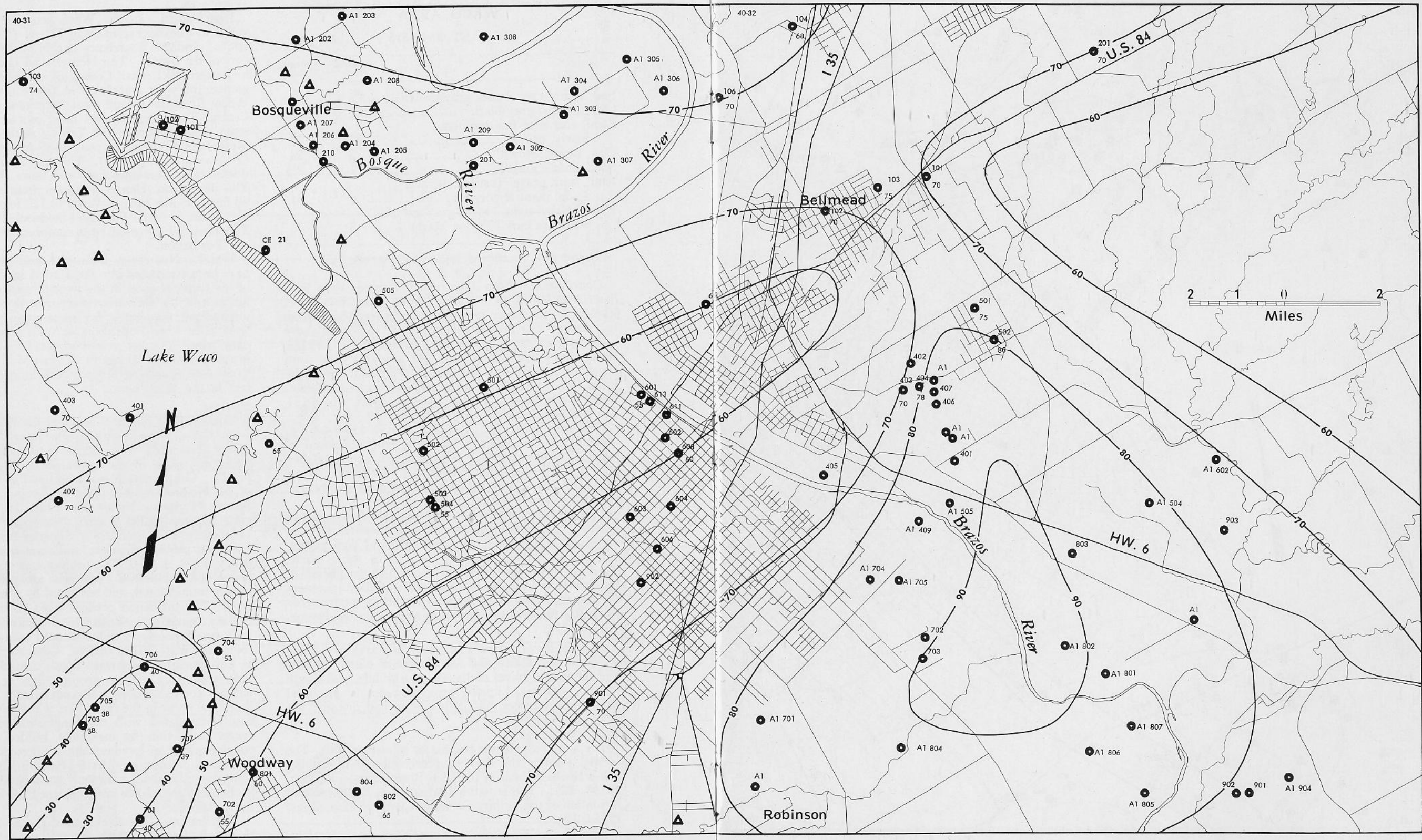


Fig. 11. Isopach, Hensel Formation.

● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 10 ft.



● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 10 ft.

Fig. 12. Net producing sand, Hensel Formation.

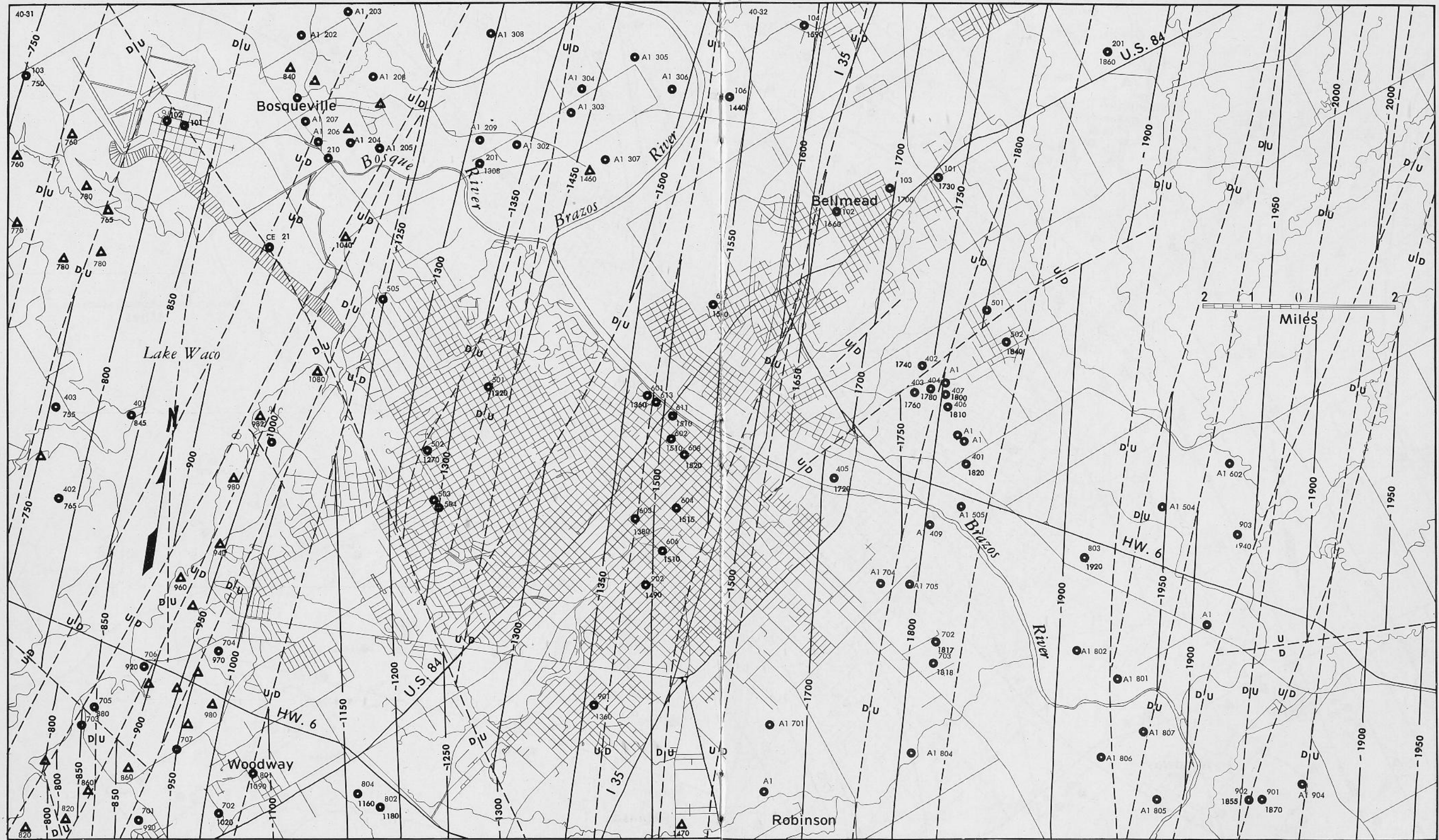


Fig. 13. Geologic structure on top of Hosston Formation.

502 Well Structural contours (based on top of Georgetown) D = Downthrown ● Well location ▲ Projected point
 1270 Depth of formation (sea level datum) - - - Fault U = Uprthrown ● A1 202 alluvial well ● 505 other well Contour interval 50 ft.

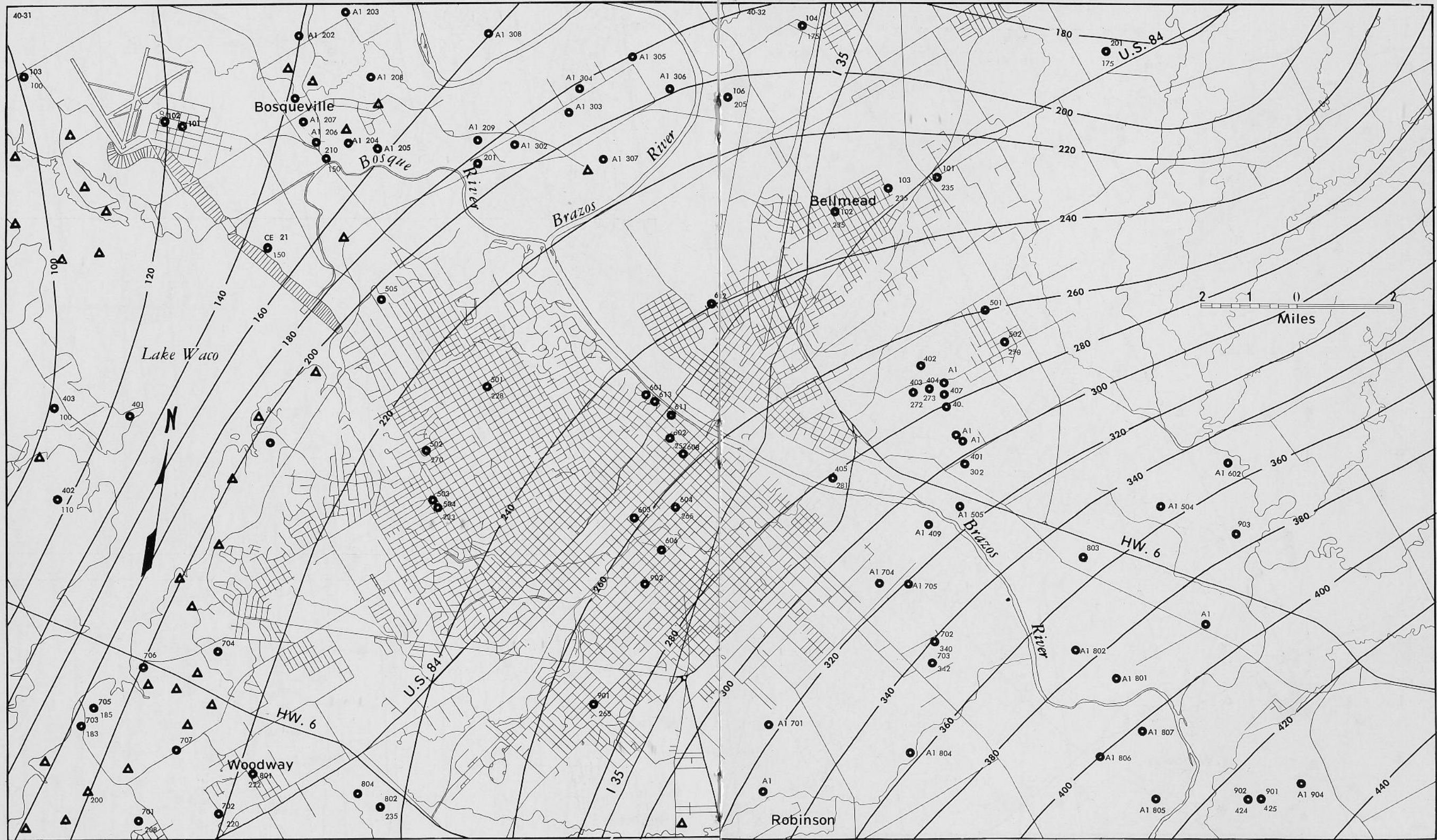


Fig. 14. Isopach, Hosston Formation.

● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 20 ft.

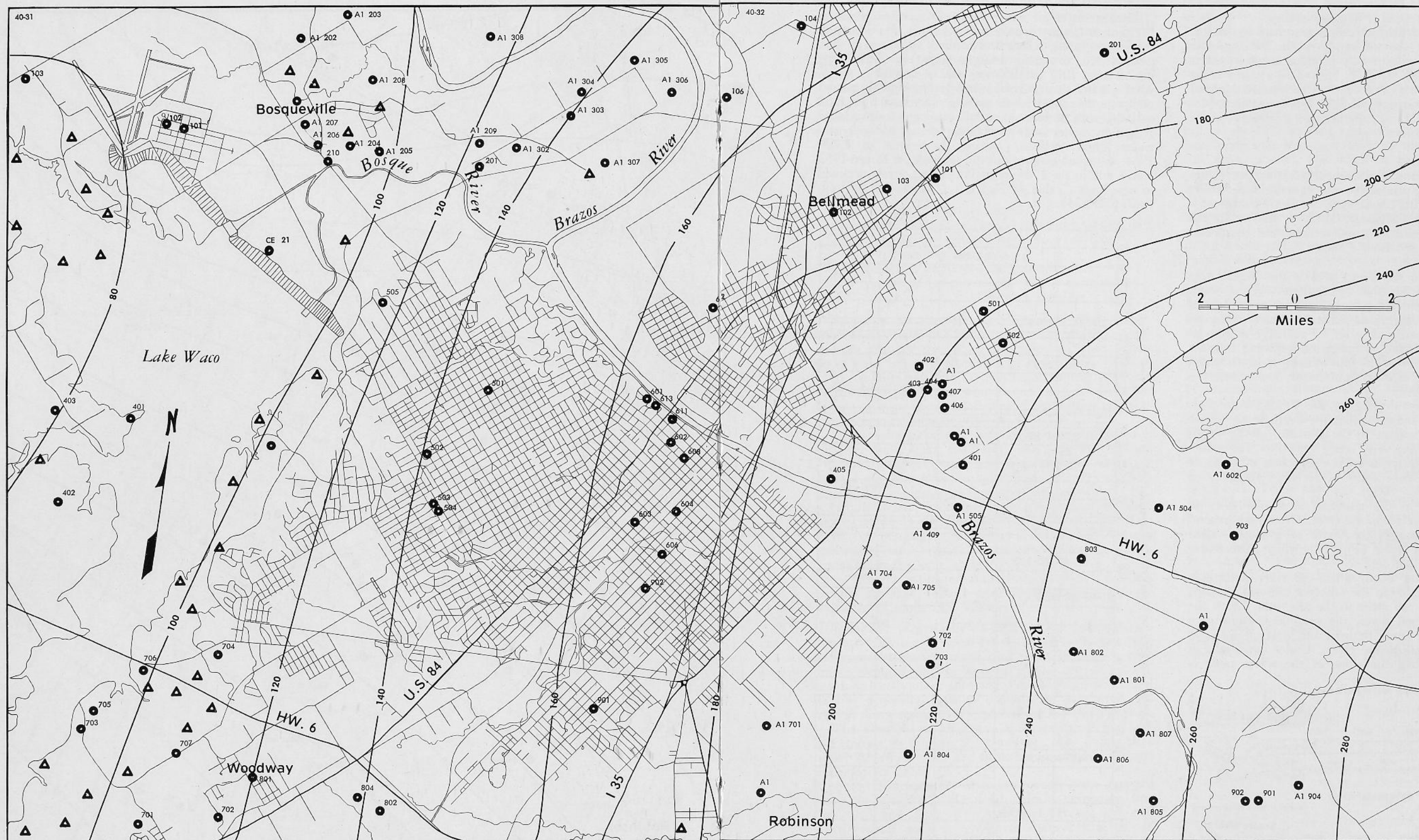


Fig. 15. Net producing sand, Hosston Formation.

● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 20 ft.

public and industrial artesian wells of Waco produce from this aquifer. In the Waco area water produced from the Hosston sand is of good quality.

Artesian wells drilled into the lower part of the formation encounter coarser sands which have greater permeability and consequently produce larger amounts of water (Holloway, 1961, p. 16). The net producing sand (Fig. 15) varies from 20 feet in western McLennan County (McGregor) to 300 feet in eastern McLennan County (Mart); the average thickness for the Waco area is 200 feet.

HYDROLOGY

SHALLOW AQUIFERS

Deposits of coarse, clean, unconsolidated gravel are probably the most productive and valuable water-bearing formations, with coarse sand the second most productive formation (Meinzer, 1942, p. 396). In the Waco area both alluvium and terraces are comprised largely of gravel and sand (Tables 7, 8).

Alluvium

The alluvium in the Waco area is the largest producer of water from shallow aquifers. Water from alluvial sands is derived principally from underflow of the river, bank storage, and infiltration from precipitation. A small quantity of water for recharge of alluvial sands is derived from drainage of adjacent terraces and from storm runoff in intermittent streams which discharge into the alluvial bottoms or flow across the alluvium to the river.

Movement. Test-drilling by the Texas Water Development Board indicates that the depth to the water level below land surface in the alluvium of the Waco area ranges from five to 40 feet (Table 7). The movement of ground water is in the direction of slope of the water table, from areas of recharge to areas of discharge.

Ground water in the alluvium is normally at or above the water surface of the river. From high ground near the valley margin the water table slopes down toward the Brazos River (Fig. 16), which gains water from the alluvial bottoms.

However, during flood, when the river surface is above the water table in the adjacent alluvial deposits, water flows from the river to the alluvium. With the passage of the flood wave, the original configuration of the water table again returns, and water flows from the alluvial aquifers to the river. Under conditions of normal stream flow, the slope of the water table is

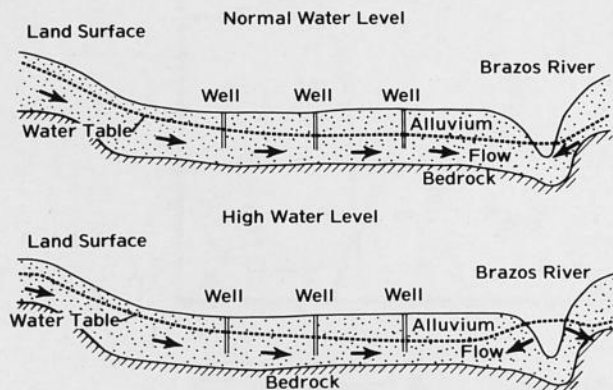


Fig. 16. Direction of ground-water flow in the alluvium near the Brazos River during normal and high-water levels.

about three feet per mile toward the river (Cronin and Wilson, 1967, p. 28).

Measurements of water levels in selected wells in McLennan County are shown in Figure 17. Generally the hydrographs reflect the rainfall (Table 4). For example, an extended drought ended in 1957. The period from 1957 to 1960 was one of normal to somewhat greater than normal rainfall. During this period pumpage decreased while recharge increased. In 1962 to 1964, with decreased rainfall, pumpage increased as irrigation water was withdrawn, and consequently water levels declined. During the winter of 1963-1964, water-table elevations did not recover to pre-1963 levels, and in the 1964 irrigation period, levels declined to new lows (Table 4; Fig. 17) (Cronin and Wilson, 1967, p. 28, 34).

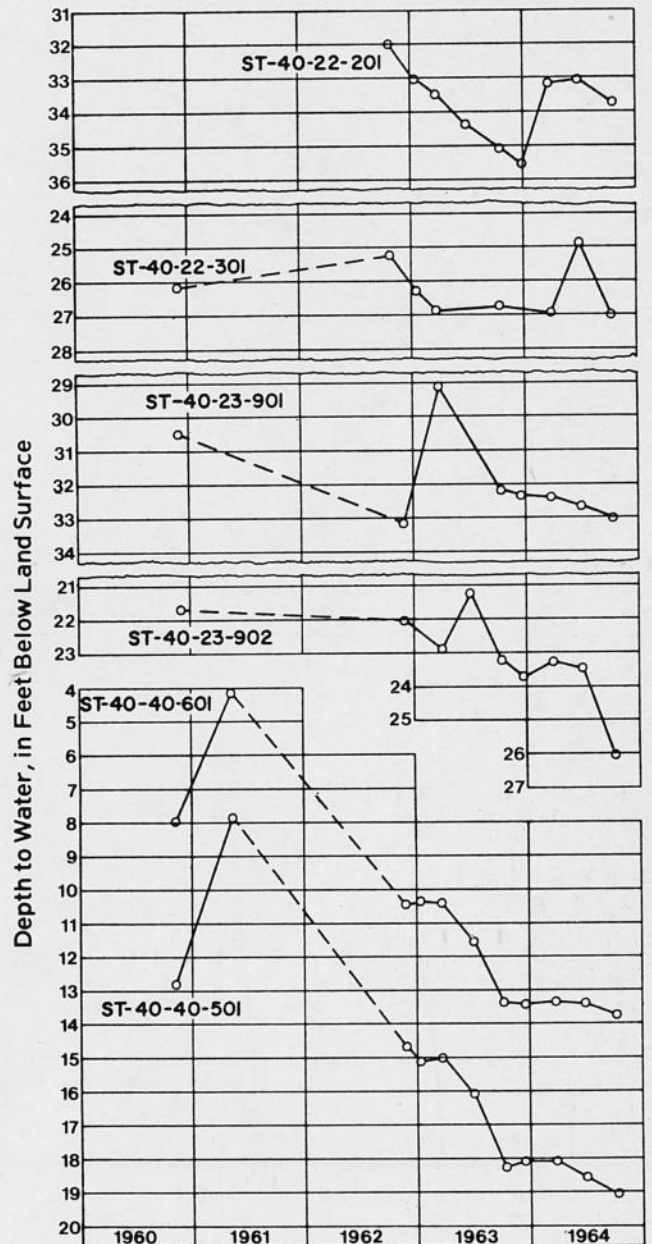


Fig. 17. Hydrographs of selected wells in McLennan County. Adapted from Cronin and Wilson, 1967, p. 41.

The rate of ground-water movement is relatively slow and proportional to the permeability of the water-bearing material and slope of the water table. Accordingly, in flood-plain alluvium, this rate usually varies from place to place due to the differences in the permeability of the water-bearing materials and changes in the hydraulic gradient. If the permeability and porosity of the water-bearing materials and the slope of the water table at a particular locality are known, the average velocity of the ground water percolating through the materials can be computed by formula:

$$v = \frac{PI}{7.48p}$$

in which

- v = velocity in feet per day
- P = permeability in gallons per day per square foot
- I = slope of the water table in feet per foot, expressed as a ratio
- p = porosity, expressed in percentage
- 7.48 is a factor for converting gallons to cubic feet. (Wenzel, 1942, p. 71)

Recharge for the alluvium, estimated from water-level fluctuations, has been estimated at 100,000 acre-feet per year for the 565 square miles of Brazos River flood plain below Waco (Cronin and others, 1963, p. 119). If the recharge is distributed evenly over the entire flood plain, this would equal 177 acre-feet per square mile, or about 3.5 inches of infiltration per year (Cronin and Wilson, 1967, p. 44-45).

Some recharge may be induced by pumpage of large capacity wells near the river, reversing the normal gradient; however, since few large capacity wells are located near the river in the area of the current study, this is not a significant recharge mechanism.

Ground-water discharge from alluvium takes place most commonly by evaporation, transpiration, spring flow, and pumpage. Some losses come about through infiltration into bedrock, but in the Waco area such losses must be very small. Actual losses in specific cases may be estimated from transmissibility and hydraulic gradient, though generally such data are not available (Cronin and Wilson, p. 44-45).

Quantity. Essentially all of the water pumped from Brazos alluvium is used for irrigation. While there are numerous domestic and stock wells, these make only minor demands on the aquifer. Sand and gravel operations locally make substantial demands on water, but this is generally obtained from their own pits, and return flows account for essentially all of the pumpage.

The locations of irrigation wells in the Waco area are shown in Figure 9. However, only Waco area wells for which data are available are numbered and included in Table 7.

About 150 acre-feet of ground water were pumped from the alluvium of the flood plain for irrigation during 1963 and 1964. The estimated acreage irrigated with ground water in 1964 was about 217 acres. In areas where few irrigation wells were in operation, pumpage was based on field estimates of acres irrigated and on use of the water (Cronin and Wilson, 1967, p. 50, 51). Approximately 112,000 acre-feet of ground water were stored in the alluvium of the flood plain of McLennan County in the spring of 1963 (Cronin

and Wilson, 1967, p. 73).

In any discussion of availability of ground water, one of the most important elements to consider is the rate of recharge to the aquifer. At the end of the drought period in 1957, the water table was at its lowest level for the recorded period (Tables 4, 9). However, during the four-year period 1957 to 1961 (a period of above-normal precipitation), the water levels rose to or above those established earlier.

This indicates rapid recharge of the alluvium by rainfall. If the 1957 to 1961 recharge rate of 177 acre-feet per square mile may be considered representative, then this same amount, equivalent to about 3.3 inches of precipitation, is available for routine use, for each square mile of flood-plain area.

The preceding estimates of recharge indicate that intermittent lowering of the water table by large withdrawals of water for short periods of time might be offset if followed by periods of normal or above normal rainfall with increasing recharge and decreasing pumpage. However, continuous withdrawals of ground water in excess of recharge would result in a lowering of the water table accompanied by a decrease in the yield of the wells due to the decrease in saturated sections of the water-bearing materials.

In some sections of the Waco area, as indicated by the locations of the wells (Fig. 9), the ground water in the alluvium is little used. Although the total amount of ground-water storage in the alluvium is important, of equal or greater importance is the amount in storage in sections of the Waco area where large quantities of ground water are being pumped for irrigation.

Quality. Fourteen McLennan County alluvial wells, of which two are within the Waco area, and one surface source were chemically analyzed (Tables 10, 11; Appendix I). These chemical analyses are shown graphically in Figure 18. This is a modified Stiff diagram, in which horizontal lines represent specific ions, and a vertical line is the zero for all ions. Anions are plotted to the right, cations to the left, in equivalents per million (epm). The figure formed by joining concentration values by straight lines is easily recognized, and may be characteristic of water from a given aquifer.

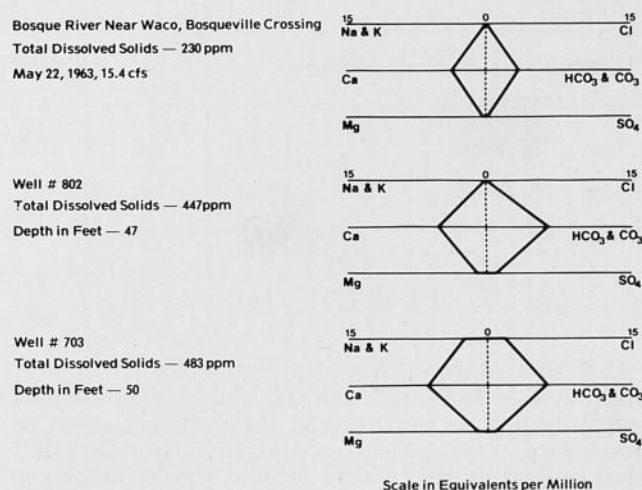


Fig. 18. Chemical quality of water from selected sites in the Brazos River valley. After Cronin and Wilson, 1967, p. 53.

TABLE 9. WATER LEVELS IN WELLS IN THE BRAZOS RIVER VALLEY, WACO AREA

Date	Water level	Date	Water level	Date	Water level
Owner: E. Hicks		Well ST-40-32-401			
Dec. 5, 1960	12.11	Mar. 19, 1963	10.31	Mar. 26, 1964	12.33
May 9, 1961	5.74	July 2	10.77	June 30	12.20
Nov. 28, 1962	10.50	Oct. 8	12.52	Oct. 8	13.68
Jan. 16, 1963	10.47	Dec. 17	13.04		
Owner: —		Well ST-40-32-409			
Dec. 5, 1960	21.69	Mar. 20, 1963	21.06	Mar. 26, 1964	23.24
May 10, 1961	19.28	July 1	21.62	June 29	23.39
Nov. 27, 1962	20.40	Oct. 7	22.33	Oct. 8	24.72
Jan. 16, 1963	22.96	Dec. 17	22.67		
Owner: Dave Simon		Well ST-40-32-703			
Nov. 27, 1962	16.44	Oct. 7, 1963	17.53	May 25, 1964	17.10
Jan. 16, 1963	15.07	Dec. 17	17.89	June 29	17.11
Mar. 19	14.80	Mar. 26, 1964	17.59	Oct. 8	22.79
Owner: O. Youngblood		Well ST-40-32-802			
Nov. 17, 1960	27.22	Mar. 19, 1963	28.56	Mar. 26, 1964	29.33
Nov. 28, 1962	27.29	Oct. 8	29.36	June 30	28.57
Jan. 16, 1963	27.42	Jan. 17, 1964	29.73	Oct. 9	28.60
Owner: Smith and Poage		Well ST-40-32-902			
Nov. 17, 1960	13.03	Oct. 8, 1963	17.49	Mar. 26, 1964	17.23
Jan. 16, 1963	15.44	Dec. 12	17.33	June 30	17.19
Mar. 19	15.68				

After Cronin and Wilson, 1967, p. 179-180.

However, study of diagrams of samples from various alluvial wells shows wide variability. Though the principal cation is calcium, and the dominant anion is bicarbonate, concentration variations clearly reflect differences in evaporation, rates of flow, aquifer lithology, and contamination.

The Texas Water Development Board and Brazos River Authority daily collected samples at U.S. Geo-

logical Survey stations during the year 1963 to determine the discharge-weighted-average chemical analysis for the Brazos River (Table 10). Figure 18 shows a graphic representation of the weighted-average analyses of water collected from the Bosque River, a tributary to the Brazos River in the Waco area. A graphic representation of these weighted-sampling locations is shown in Figure 10.

TABLE 10. CHEMICAL ANALYSES OF SURFACE WATER IN THE LOWER BRAZOS RIVER BASIN

(Analyses are in parts per million except specific conductance, pH, percent sodium, and sodium-adsorption ratio.)

Location	Measured discharge (cfs)	Date of collection	Silica (SiO ₂)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	Sodium-adsorption ratio (SAR)	Dis-solved solids (calculated sum)	Total hardness as CaCO ₃	Percent sodium	Specific conductance (micromhos at 25° C)	pH
Bosque River near Waco	15.4	May 22, 1963	4.8	53	5.8	24	162	39	23	.4	.05	.8	230	156	25	391	6.8

After Cronin and Wilson, 1967, p. 59.

TABLE 11. CHEMICAL ANALYSES OF WATER FROM WELLS AND SPRINGS IN THE BRAZOS RIVER VALLEY, McLENNAN COUNTY

(Analyses are in parts per million except specific conductance, pH, percent sodium, and sodium-adsorption ratio.)

Well	Depth of well (ft.)	Date of collection	Silica (SiO ₂)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	Boron (B)	Dis-solved solids	Hardness as CaCO ₃	Percent sodium	Sodium-adsorption ratio (SAR)	Residual sodium carbonate (RSC)	Specific conductance (micromhos at 25° C)	pH
ST-40-22-201	41	July 1, 1963	11	0.03	113	4.4		*31	316	19	34	0.2	50	—	418	300	18	0.8	0.00	693	6.9
1	32	do	28	.02	300	71		*236	510	352	518	.3	46	0.35	1,800	1,040	33	3.2	.00	2,810	6.6
1	22	Apr. 24, 1958	15	—	91	12		*5	256	43	25	—	18	.17	432	273	—	.5	.00	646	6.9
1	32	July 1, 1963	15	—	100	15		*21	328	35	26	.2	—	—	391	311	13	—	.00	—	—
1	32	Jan. 31, 1955	—	—	60	52		*0	375	22	14	—	—	—	523	351	7	—	.00	599	7.2
1	32	Mar. 20, 1963	16	—	65	38		*11	376	17	6.0	.6	9.1	—	348	318	7	.3	.00	763	6.8
804	42	Aug. 3, 1964	19	1.6	117	25	17	1.8	414	51	26	.4	.5	.11	462	395	9	.4	.00	825	7.0
32-703	50?	May 10, 1961	19	—	113	7.2	48	1.6	318	46	67	.1	25	.25	483	312	25	1.2	.00	721	6.6
802	47	July 29, 1963	17	2.2	115	19	—	*23	394	48	29	.4	1.2	.08	447	365	12	.5	.00	816	6.6
40-202	38	May 10, 1961	15	—	135	4.5	33	.9	358	49	36	.5	50	.22	500	356	17	.8	.00	911	7.0
502	35	July 12, 1963	18	.02	138	11	—	*48	420	84	33	.7	17	.24	557	390	21	1.1	.00	1,100	7.0
505	35	do	19	—	145	10	—	*103	424	123	96	.4	18	.32	723	408	36	2.2	.00	—	—
507	35	Apr. 24, 1958	19	—	147	16	—	*125	499	182	76	—	—	—	1,045	385	—	—	.00	1,180	7.1
509	44	May 10, 1961	20	—	122	40	77	3.0	438	149	97	.4	2.5	.16	726	469	26	1.5	.00	1,340	7.7
601	28	do	18	—	142	26	116	2.6	428	151	107	.3	76	.31	849	462	35	2.3	.00	—	—
802	22	July 10, 1963	17	.00	156	6.3	—	*67	364	83	66	.4	101	.48	676	415	26	1.4	.00	1,020	6.9

*Sodium and potassium calculation as sodium (Na).
 †Analysis by State Chemist, Texas A&M University.
 After Cronin and Wilson, 1967, p. 201.

The Bosque River sample analysis shown on Table 11 (May 22, 1963) indicates dissolved solids concentrations of 230 ppm (at the sampling point) and calcium and bicarbonate as the major cation and anion. This river has its origin outside the Waco area and its course crosses limestone rocks of Cretaceous age. The chemical quality of the Bosque River water should not affect the alluvial ground water as it is an effluent stream where it crosses the alluvium of the flood plain.

Recharge from the Brazos River in flood stage influences the chemistry of flood-plain ground water. Pumping may also induce local chemical changes through recharge but as a general rule this is not the case. Over most of the flood plain the water table slopes toward the river, therefore the chemical composition of the Brazos River does not affect the quality of the flood-plain water. Analysis of Brazos River water indicates that the major cation and anion are sodium and bicarbonate, and that dissolved solids in water from bedrock aquifers is lower in concentration than it is in the alluvium (Cronin and Wilson, 1967, p. 63).

Table 12 lists standards for drinking water. Water from alluvial wells exceeds the maximum values for dissolved solids in 80 percent of the analyses. Iron is also present in excess, as are chloride and sulfate.

TABLE 12. DRINKING WATER STANDARDS

Constituent	Suggested maximum concentration (ppm)
Chloride -----	250
Fluoride -----	0.8 to 1.0
Iron -----	0.3
Manganese -----	0.05
Nitrate -----	45
Sulfate -----	250
Total dissolved solids -----	500

Based on annual average of maximum daily air temperature of 78.1° F. at Waco. *After* Cronin and Wilson, 1967, p. 64.

Based on a general hardness scale (U.S. Public Health Service), practically all of the water in the flood plain alluvium is hard or very hard (Tables 11, 13).

TABLE 13. WATER HARDNESS RANGE

ppm Ca-Mg	type
0 to 60	Soft
61 to 120	Moderately hard
121 to 180	Hard
More than 180	Very hard

The optimum fluoride concentration (dependent upon mean annual air temperature) is 0.7 to 0.8 ppm (U.S. Public Health Service). In the alluvium of McLennan County this concentration varies from 0.1 to 0.7 ppm, with most concentrations under 0.7 ppm (Table 11) (Cronin and Wilson, 1967, p. 65).

The concentration of nitrates in drinking water should not exceed 45 ppm or it can be potentially dangerous to infants (McKee and Wolf, 1963, p. 113; Heller, 1933, p. 22). This limit was exceeded by at least five wells (Table 11).

The suitability of irrigation water is judged by (1) sodium adsorption ratio, (2) boron content, and (3) residual sodium carbonate (U.S. Salinity Laboratory Staff, 1954, p. 79-81). From the alluvial wells about 60 percent of all water samples tested ranked as low-sodium, high-salinity hazard waters. About 30 percent of waters ranked as low-sodium, medium-salinity hazard. One sample ranked as low-sodium, very-high-salinity hazard.

A classification of water by boron content is shown in Table 14. None of the 14 samples for the Waco, McLennan County, area exceeds 1.0 ppm (Table 11). Boron is not a problem in the local flood-plain alluvial water.

TABLE 14. WATER CLASSIFICATION BY BORON CONTENT

Classes of water Rating Grade	Sensitive crops (ppm)	Semitolerant crops (ppm)	Tolerant crops (ppm)
1 Excellent	Less than 0.33	Less than 0.67	Less than 1.00
2 Good	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
3 Permissible	0.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4 Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5 Unsuitable	More than 1.25	More than 2.50	More than 3.75

Cronin and Wilson, 1967, p. 70.

Wells. Drilling of wells into flood-plain alluvium has not changed significantly since 1963. Although large amounts of water are withdrawn every year, this amount does not exceed the storage capacity of 112,000 acre-feet per year or even the recharge capability of 100,000 acre-feet per year as estimated by Cronin and others (1963, p. 119). Rainfall readily replenishes the alluvium. In years of low rainfall heavy usage takes place lowering the water table. This is balanced out by the years of normal or heavy rainfall when the usage of water from the alluvium decreases. However, caution should be taken in prolonged drought years that over usage does not cause collapse of the water-bearing formations, thus damaging the recharge capabilities of the alluvium.

Depth of wells. Wells in the alluvium are shallow, extending only a few feet below the water surface and penetrating the alluvial section usually to about two to five feet into the bedrock. Depending on location and topography this depth may be up to 50 feet.

Productive capacity of wells. Measured permeability of alluvium ranges from 0.001 to 18,000 gpd per square foot (Cronin and Wilson, 1967, p. 25).

Wells in McLennan County (1963 and 1964) range in capacity from six to 134 gpm per foot of drawdown. Although none of these test wells lies within the immediate Waco area, the data give an idea of reasonable local values (Cronin and Wilson, 1967, p. 27).

Development of wells. To find the most favorable location for a well, several test holes are generally drilled to determine the thickness and particle size of the water-bearing formation. Production wells are usually drilled two to five feet into the bedrock. Hole diameter varies from 36 to 42 inches and is cased throughout. In older wells 18-inch casing is corrugated galvanized culvert pipe, with one-half inch woven-wire screen opposite the coarser sand and gravel. Most of these wells have been reworked, and torch-

slotted steel liners have been inserted into the old casings. Today most wells are cased with 14- to 18-inch (diameter) torch-slotted steel pipe, packed outside with pea gravel to fill the space between the casing and well hole. Pump tests determine if the packing is adequate. The capacity of the well and pump size are also determined by pump test (Cronin and Wilson, 1967, p. 47). In the Waco area most wells are equipped with six- to eight-inch turbine pumps set approximately two feet from the bottom of the well. The power unit is usually an internal combustion engine.

Pumping tests conducted in the alluvium south of Waco during the 1963 to 1964 irrigation season showed about half of the wells had yields in the 250- to 500-gpm range; half of the specific capacities were below 25 gpm per foot of drawdown. While these tests were not in the Waco area, it is probable that similar specific yields occur here as well.

Drawdowns are increased by pumpage of closely-spaced wells, and yields are reduced. Using (1) transmissibility of 20,000 to 40,000 gallons per day per foot, (2) a storage coefficient of 15 percent (specific yield), and (3) total withdrawal of water from storage, the cones of depression of pumping wells in the alluvium can be approximated (Cronin and Wilson, 1967, p. 48). Drawdown curves for wells pumping for 30 days at

rates ranging from 250 to 1500 gpm are shown in Figure 19. Note particularly the effects of varying transmissibility and distance from pumping wells.

TABLE 15. SPECIFIC CAPACITY AND YIELD OF IRRIGATION WELLS IN THE FLOOD-PLAIN ALLUVIUM OF THE BRAZOS RIVER, 1963-64

Yield			Specific capacity		
Range (gpm)	No. of measurements	Proportion in range (percent)	Range (gpm per foot of drawdown)	No. of measurements	Proportion in range (percent)
Less than 250	40	9.8	Less than 25	196	55.8
250 to 500	206	50.5	25 to 50	116	33.0
500 to 750	117	28.7	50 to 75	23	6.6
750 to 1,000	26	6.4	75 to 100	10	2.8
1,000 +	19	4.7	100 +	6	1.7
Total	408	100	—	351	100

After Cronin and Wilson, 1967, p. 48.

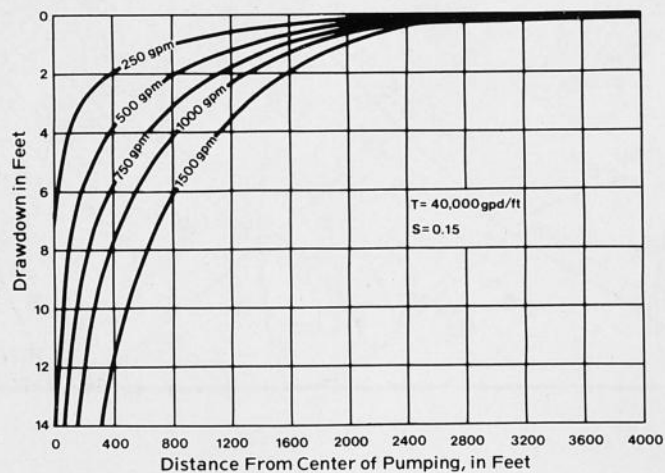
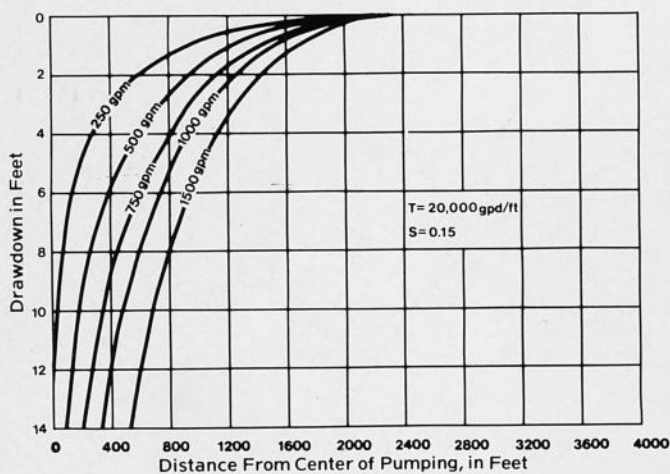


Fig. 19. Theoretical drawdown caused by a well pumping continuously for 30 days. After Cronin and Wilson, 1967, p. 49.

Terraces

Some water is produced from shallow wells in larger terraces, but the supply is limited and is most available only during the wet season. These terraces are sufficiently permeable to provide excellent subsurface disposal of small quantities of waste water.

Ground water is derived from some isolated terrace alluvium where well depths indicate deposits as much as 40 feet thick. The position of terraces bordering the flood-plain alluvium along the river is shown in Figure 9, where the surface of the bordering terraces, which usually slopes toward the river, ranges from about 10 to 30 feet above the surface of the flood-plain alluvium. Where the terrace is hydraulically connected to the flood-plain alluvium, terraces contribute water directly into the flood-plain alluvium by underflow. The amount of ground water moving from the bordering terraces into the flood-plain alluvium depends not only on the thickness of the saturated zone but also on the gradient of the water table and permeability of the saturated material. Permeability of the water-bearing materials of the terraces is not well known, but samples from test holes and the yields of some wells indicate that it is rather low. This suggests that the amount of water moving from the terraces into the flood-plain alluvium is rather small.

DEEP AQUIFERS

In the Waco area artesian water is obtained from two major Cretaceous aquifers, the Hensel and Hosston Formations of the Trinity Group. Of these two sands, the Hosston is by far the more productive.

Hensel

Ground water from the Hensel Formation in Waco originates at the outcrop area in Comanche and adjacent counties (Fig. 2). This outcrop area is about 70 miles west of Waco, at the western boundary of the Trinity Basin.

Movement. Infiltration water percolates down the Cretaceous aquifer to reach the Waco area with considerable hydrostatic pressure (Figs. 5, 20, 21). The journey takes some tens of thousands of years. Although hard water at origin, this flow reaches Waco as

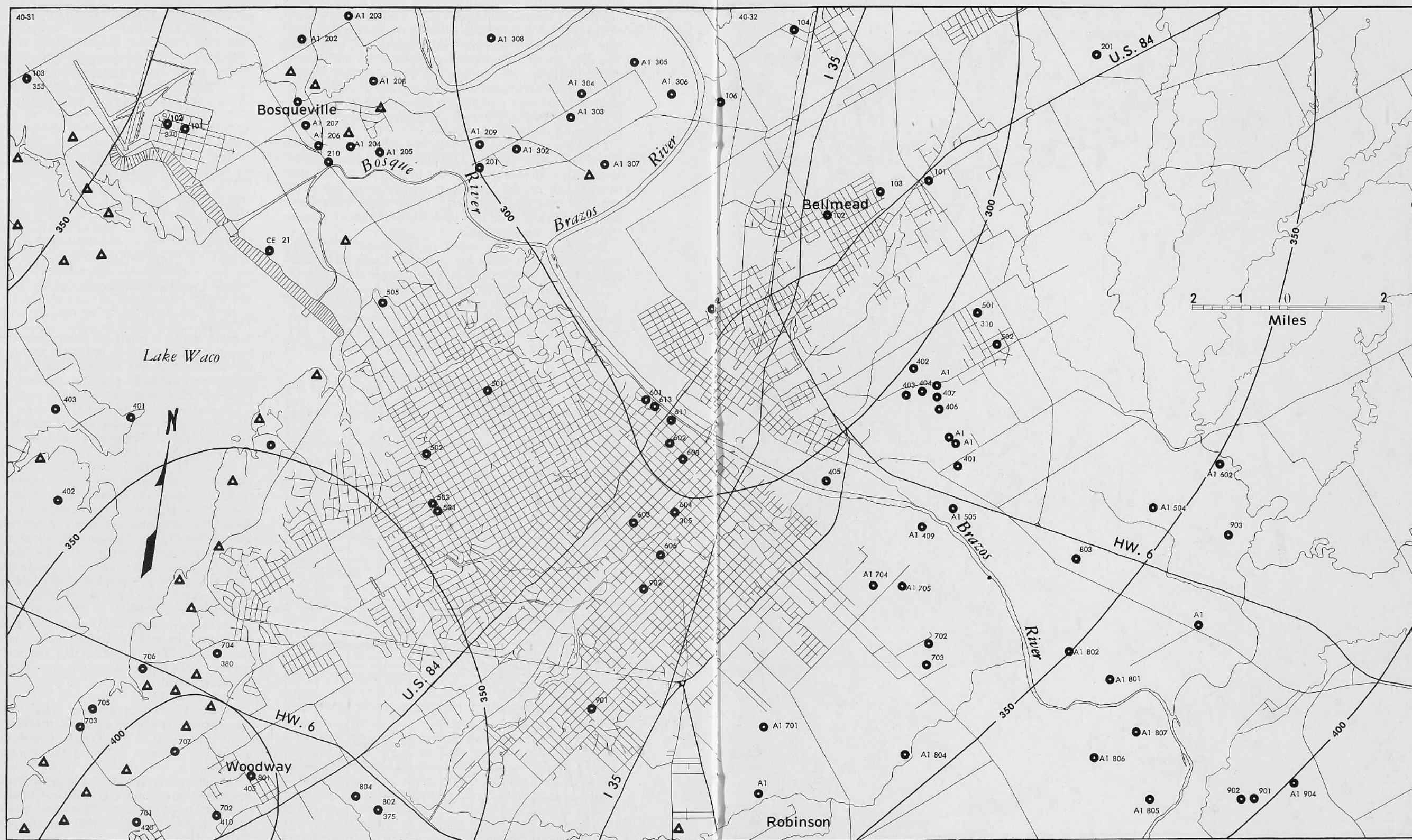


Fig. 20. Piezometric surface, Hensel Formation, 1972. Data from Texas Water Development Board observation wells.

Data from Texas Water Development Board Observation Wells.

- Well location
- A1 202 alluvial well
- 505 other well
- ▲ Projected point
- Contour interval 50 ft.



Fig. 21. Piezometric surface, Hosston Formation, 1972. Data from Texas Water Development Board observation wells.

● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 50 ft.

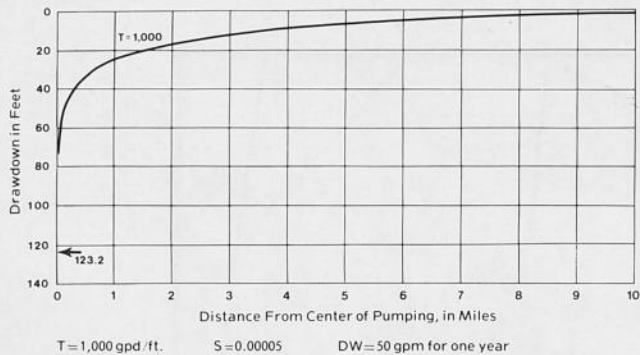


Fig. 22a. T=1,000 gpd/ft. S=0.000025. Drawdown calculated for a well or group of wells pumping 50 gpm for one year, assuming an aquifer of infinite areal extent.

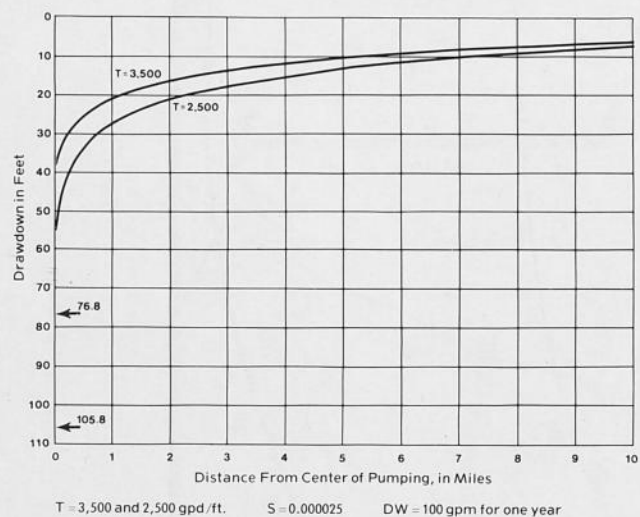


Fig. 22b. T=3,500 and 2,500 gpd/ft. S=0.000025. Dw=100 gpm for one year.

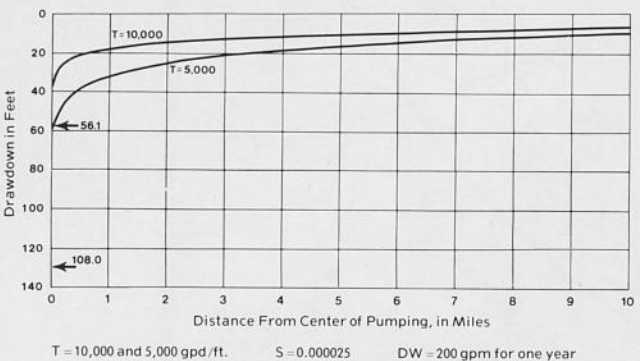


Fig. 22c. T=10,000 and 5,000 gpd/ft. S=0.000025. Drawdown calculated for a well or group of wells pumping 200 gpm for one year, assuming an aquifer of infinite areal extent.

Fig. 22. Relation of decline in water levels to transmissibility and distance in the Hensel Formation. T=Coefficient of transmissibility in gpd/ft. S=Coefficient of storage. Dw=drawdown, calculated for a well or group of wells pumping for one year. These conditions assume an aquifer of infinite extent. Adapted from TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975.

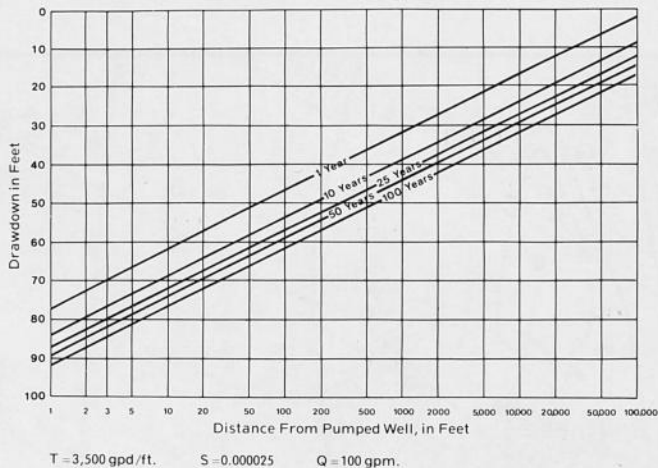


Fig. 23. Relation of decline in water levels to time and distance as a result of pumping from the Hensel Formation under artesian conditions.

soft, potable water (Table 13). Figure 22 relates drawdown rates (50, 100, and 200 gpm for one year) to decline in water levels and transmissibility and distance. Figure 23 gives the relationship of decline in water levels to time and distance as a function of pumping under artesian conditions.

Quantity. The quantity of water available from the Hensel sand (Table 16) can only be estimated, and except for Woodway, little is used in the Waco area.

TABLE 16. ESTIMATED USE OF GROUND WATER FROM THE PRINCIPAL AQUIFERS IN CENTRAL TEXAS

GEOLOGIC SOURCE	Public Supply Acre-Feet	Industrial Acre-Feet	Irrigation Acre-Feet	Domestic, Rural and Stock Acre-Feet	Total Acre-Feet
Hensel and Hosston Formations	16,816	3,659	16,099	5,870	42,444
Glen Rose Formation	—	—	—	1,235	1,235
Paluxy Formation	61	1	—	1,034	1,096
Edwards Formation	2,104	232	33	930	3,299
Woodbine Group	124	109	—	347	580
TOTAL	19,105	4,001	16,132	9,416	48,654

After TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 18.

Most aquifer potential lies west of Waco, where it is the major aquifer. Woodway has six wells completed into the Hensel Formation. Three wells, with a capacity of 500 gallons per minute each, are pumped year round, and three, with a capacity of approximately 150 gpm each, are pumped intermittently. Two wells completed into the Hosston Formation, are pumped in the summer months only (June to September), and their capacities vary from 100 to 150 gallons per minute.

Test data for the Hensel Formation east of Waco

TABLE 17. RESULTS OF PUMPING TESTS CONDUCTED ON WELLS IN WACO, McLENNAN COUNTY

State Well No. of test well(s)	Aquifer	Coefficient of transmissibility from test (gpd/ft.)	Effective sand thickness (feet)	Coefficient of permeability (gpd/ft. ²)	Total fresh water sand thickness (feet)	Approximate coefficient of transmissibility (gpd/ft.)
ST-40-16-404 ¹	Kho	1,950	107	18	120	2,200
ST-40-16-501	Kho	1,300	50	26	140	3,600
ST-40-24-102	Kho	2,500	79	32	115	3,600
ST-40-24-801 ¹	Kho, Kpe	2,900	135	21	191	4,100
ST-40-24-802 ¹	Kho, Kpe	2,700	111	24	191	4,600
ST-40-24-803 (2/11/53)	Kho	3,100	165	19	165	3,100
ST-40-24-803 (3/31/64)	Kho	3,300	165	20	165	3,300
ST-40-31-601 ²	Kho	6,500	—	—	—	—
ST-40-31-701	Kho	5,500	62	89	124	11,000
ST-40-32-403 ²	Kho	4,500	140	32	195	6,300
ST-40-37-501	Khe	1,100	43	26	43	1,100
ST-40-39-106	Kho	5,700	72	79	125	9,900
ST-40-39-702	Kho	9,100	91	100	152	15,200
ST-40-46-403	Kho	8,200	115	71	115	8,200
ST-40-46-801 ¹	Kho	5,600	59	95	89	8,400

State Well No. of test well(s)	Aquifer	Coefficient of storage	Drawdown or recovery (feet)	Time after well turned on or off (hours)	Average yield (gpm)	Specific capacity in gpm/ft.
ST-40-16-404 ¹	Kho	—	138.0	1.17	250.0	1.8
501	Kho	—	119.0	2.00	100.0	0.8
24-102	Kho	—	122.0	4.00	135.0	1.1
801 ¹	Kho, Kpe	—	—	1.37	560.0	—
802 ¹	Kho, Kpe	—	—	1.38	513.5	—
(2/11/53) 803	Kho	—	447.0	94.00	650.0	1.5
(3/31/64) 803	Kho	—	314.0	8.00	768.0	2.4
31-601 ²	Kho	0.000062	—	—	—	3.7
701	Kho	0.000066	—	—	—	—
32-403	Kho	—	—	48.00	—	2.1
37-501	Khe	—	201.0	5.00	155.0	0.8
39-106	Kho	—	248.0	6.00	580.0	2.3
702	Kho	—	71.0	2.66	191.0	2.7
46-403	Kho	0.000028	—	—	—	—
801 ¹	Kho	—	43.0	66.00	100.0	2.3

Aquifer: Khe, Hensel Formation; Kpe, Pearsall Formation; Kho, Hosston Formation.

Transmissibility values shown are the average of drawdown and recovery values computed from test data unless indicated by footnotes.

¹Aquifer coefficients computed from recovery test.

²W. O. George and B. A. Barnes, 1945.

Adapted from TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975, vol. 1, p. 13.

(Table 17) show permeability coefficients from 26 to 126 gpd per square foot (TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975, vol. 1, p. 12).

In the Hensel aquifer, transmissibility varies from zero to 15,000 gpd per foot, largely because of lithologic variations (TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975, vol. 1, p. 12). However, the higher values are quite unusual. There is a general lack of test data for the Hensel sand, there-

fore the coefficient of storage is less well known, though storage values should be less than those for the Hosston Formation.

Quality. Chemical analyses of water from selected wells in the Waco area are given in Appendix I. Other constituents considered in evaluating chemical quality of water are: sodium content (4 to 65 ppm) and boron content (0.06 to 0.4 ppm) which are well within the values indicated for irrigating sensitive crops.

The water from the Hensel Formation in Woodway



Fig. 24. Projected water-level decline, Hensel Formation, 1975. Data from TWDB unpub. Trinity aquifer study—Klent, Perkins, and Alvarez, 1975.

Data: Water Development Board Unpublished Trinity Study ● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 25 ft.



Fig. 25. Projected water-level decline, Hensel Formation, 1990. Data from TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975.

Data: Water Development Board Unpublished Trinity Study
 ● Well location
 ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well
 Contour interval 50 ft.



Fig. 26. Projected water-level decline, Hensel Formation, 2020. Data from TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975.

Data: Water Development Board Unpublished Trinity Study

- Well location
- ▲ Projected point
- A1 202 alluvial well
- 505 other well
- Contour interval 250 ft.

is soft (3 to 54 ppm CaCO₃, sodium bicarbonate variety), with a present constant temperature of 110° F (43.3° C). This represents a 2° F (1.1° C) drop of the peak of the temperature over the years. The chemical quality of the Hensel water is generally good. There is, however, an increase in dissolved solids from northwest to south-southeast. Loss of permeability in the southeast restricts the influx of fresh water adding to this increase and lowering the quality of the ground water (TWDB unpub. Trinity aquifer study).

Ground water from the Hensel Formation in the Waco area is used primarily for domestic and public supply purposes. Its chemical constituents (Tables 18, 19) are generally within the range established by the U.S. Public Health standards. This is not the case for the rest of the Trinity aquifer basin where iron (0.02-2.2 ppm), fluoride (0.1-6.0 ppm), and dissolved solids (311-1,470 ppm), generally exceed these standards. Nitrates (0-64 ppm), chloride (11-344 ppm), sulfate (24-510 ppm), and hardness (3-398 ppm CaCO₃) are low over most of the area except adjacent to the calcareous facies, where they exceed U.S. Health Department standards. The only treatment to the water for the public supply systems in the area is chlorination (TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, p. 15).

Ground water from the Hensel is usable for industrial purposes except in areas where iron, hardness, and dissolved solids contents exceed the amounts for the specific use. Contamination is restricted to local areas and as a rule occurs when Glen Rose water (highly mineralized) migrates into the Hensel along fault planes or poorly completed wells. The deterioration of such wells is rapid once the process has started and is irreversible (TWDB unpub. Trinity aquifer report—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 15).

Wells. Present well development in the Hensel Formation (Fig. 20) exceeds prudent practices and further development is undesirable for the Waco area (Figs. 24, 25, 26). The present piezometric surface and the projections (Figs. 24, 25, 26) show that there has been a steady and major decline over the past years (Fig. 21), which has increased the possibility of contamination of the Hensel waters by high sulfate waters of the Glen Rose Formation.

Depth of wells. Most Hensel wells have been completed at a depth of 1,000 to 1,600 feet in the Waco area; the shallower wells are to the west and the deeper wells to the east.

Productive capacity of wells. Well design and completion in the Waco area is based on required production and economy. The capacity of these wells (as in the case of Woodway) vary from as little as 30 to as much as 500 gallons per minute.

Development of wells. Most well casings into the Hensel Formation in the Waco area range in size from three to 13¾ inches in diameter. These wells are straight walled, cased, and cemented from surface to bottom. High capacity wells are under-reamed, gravel packed, and completed with selective screens opposite the water-bearing formation. Some are cemented from top to bottom and perforated opposite the water-bearing

TABLE 18. RANGE OF CONSTITUENTS OR PROPERTIES IN THE GROUND WATER OF THE HENSEL AND HOSSTON FORMATIONS IN THE WACO, McLENNAN COUNTY, AREA

Constituents or Property	Hensel		Hosston	
Silica (SiO ₂)	10	- 15	8	- 29
Iron (Fe)	0.02	- 0.4	0.01	- 3.6
Calcium (Ca)	1	- 17	1	- 12
Magnesium (Mg)	2	- 7	0	- 16
Sodium and Potassium (Na+K)	201	- 322	202	- 350
Bicarbonate (HCO ₃)	355	- 446	320	- 555
Sulfate (SO ₄)	87	- 221	70	- 140
Chloride (Cl)	20	- 105	37	- 175
Fluoride (F)	0.4	- 2.5	0.7	- 3
Nitrate (NO ₃)	0.04	- 3	0	- 2.5
Boron (B)	—		0	- 0.4
Total dissolved solids (TDS)	549	- 890	553	- 947
Total hardness (CaCO ₃)	3	- 54	5	- 44
Percent sodium (% Na)	89	- 98	92	- 99
Specific conductance (Sp cond)	815	-1520	930	-1568
pH	7.8	- 9.1	7.9	- 8.7
Sodium adsorption ratio (SAR)	15	- 32	15	- 50

Analyses given are in parts per million except percent sodium, specific conductance, pH and sodium adsorption ratio. Single values appear where only one analysis or value was available. After TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 17.

formation. In the past, casing has been set at the top of the water-bearing formation with an "open-hole" below, but this is a poor practice. Torch-slotted screens are used where greatest economy is desired. In most public supply wells surface casing (as large as 22 inches) is cemented in place to restrict surface-water contamination (TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, p. 24).

Many problems arise from incorrect well construction techniques, such as when friable sands of the Hensel Formation clog casing slots or openings. Over pumping may cause similar problems and consequently irreparable damage to the well or pump.

Hosston

Recharge of the Hosston Formation occurs in the outcrop area (Fig. 2) which covers several hundred square miles overlain by soils of highly permeable sands and sandy clay loams. The terrain is characterized by gently sloping plains with moderate relief. Such conditions are excellent for recharge from rainfall, leakage from lakes and streams, and infiltration resulting from the irrigation of crops. The amount of recharge to the Trinity basin can only be estimated.

Simulation of recharge by the Texas Water Development Board indicated that three percent of annual precipitation actually entered the aquifer as recharge. This is about 0.1 foot per year, or 11,840 acre-feet per

year for the entire Trinity aquifer system. Even some of this water is diverted as spring flow to streams which transect the aquifer, reducing the estimated total to about 88,000 acre-feet per year. Pumpage in the outcrop area reduces this to 82,000 acre-feet per year, and additional losses derive from seepage and evaporation (TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975, vol. 1, p. 11). The exact amount of water available for the Waco area cannot now be estimated, but dropping water levels indicate that pumpage exceeds local recharge by major amounts.

Movement. Ground water in the Hosston Formation moves slowly downdip. It enters the aquifer in Comanche and adjacent counties; by the time it reaches Waco it is tens of thousands of years old. Thus effective recharge for Waco was completed during the last Ice Age.

Water level measurements indicate that the present gradient of the piezometric surface is ten to 25 feet per mile east-southeast over most of Central Texas (Fig. 21).

Water moves toward pumping wells. As a result of heavy pumpage, a major cone of depression has developed in Bell, Coryell, Hill, and McLennan Counties. The long axis of this cone parallels Interstate Highway 35, and the deepest part of the cone is at Waco.

Quantity. The amount of water that moves downdip from the outcrop to the areas of continuous pumpage was calculated by determining the transmissibility of the Trinity Group at a halfway point (Fig. 27 a, b, c). Coefficients of permeability of Hosston sands range from 17 to 171 gpd per square foot. Permeability is generally reduced adjacent to faults of the Balcones system. Average permeability coefficient of Hosston sand is about 77 gpd per square foot away from the fault zone.

Transmissibility coefficients may exceed 45,000 gpd per foot in Hosston aquifers. However, storage coefficients are very low, ranging from 0.000028 to 0.000077 (TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975, vol. 1, p. 12), thus actual stored water is small in volume, and excessive demands can quickly deplete the reservoir.

Ratio of water-level decline to distance from a pumped well is shown in Figure 27. This value varies markedly with variations in coefficients of transmissibility. The curves shown describe wells pumping at various indicated rates for a period of one year, from sands having specific coefficients of transmissibility and storage.

Note that a well pumping 50 gpm for one year, from an aquifer having a transmissibility coefficient of 1,000 gpd per foot, and a storage coefficient of 0.00005, will exhibit a cone-of-depression with a drawdown of 25 feet at a distance of one mile.

Figure 28 shows the relationship of water-table decline to pumpage time and distance from the pumping well, for artesian conditions. For water-table conditions, relationships are shown in Figure 29. Note that the rate of decline decreases with time, and is proportional to pumpage.

For Hosston wells, pumped at a rate of 300 gpm, drawdown measured 200 feet from the pumping well would be 45 feet at the end of one year, 54 feet at the

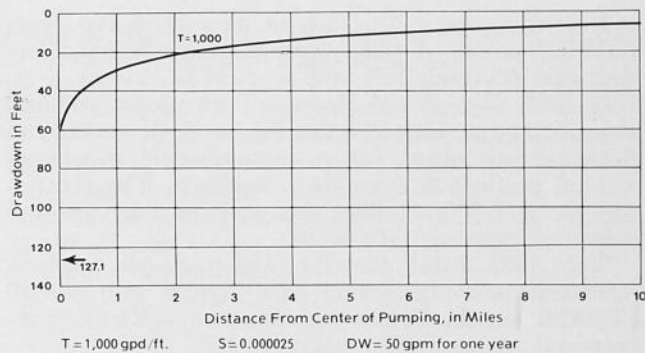


Fig. 27a. Drawdown calculated for a well or group of wells pumping 50 gpm for one year.

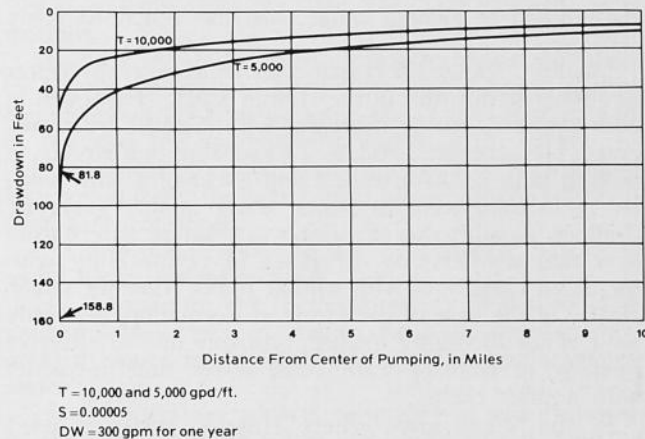


Fig. 27b. Drawdown calculated for a well or group of wells pumping 300 gpm for one year.

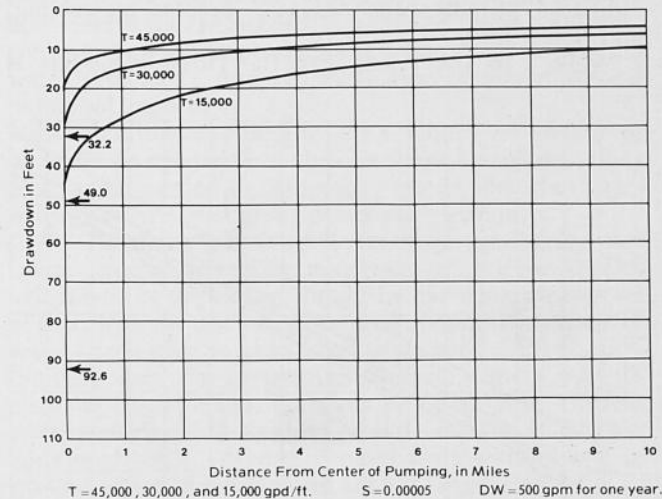


Fig. 27c. Drawdown calculated for a well or group of wells pumping 500 gpm for one year.

Fig. 27. Relation of decline in water levels to transmissibility and distance in the Hosston Formation. T=Coefficient of transmissibility in gpd/ft. S=Coefficient of storage. Dw=drawdown, calculated for a well or group of wells pumping for one year, assuming an aquifer of infinite areal extent. Adapted from TWDB unpub. Trinity aquifer study—Klemt, Perkins, and Alvarez, 1975.

end of ten years, and 61 feet at the end of 100 years (TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 12).

In 1967, Hensel and Hosston Formations produced about 5900 acre-feet of water for rural, domestic, and stock use in Central Texas, approximately 14 percent of total production from these aquifers. The remainder, about 36,000 acre-feet, was used for municipal and industrial purposes (Table 16).

Since 1955, rural, domestic, and stock use has been relatively constant, varying only slightly with rainfall (TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 16).

Although the overall population has decreased (Texas Almanac, 1972-73) in rural areas, the individual water use of each farm and ranch has increased. This may be directly related to modernization. Therefore, the amount of ground water used has remained fairly constant.

Quality. Down dip Hosston water is generally better in quality than water in the Hensel Sand. However, in both aquifers, quality decreases with distance from outcrop (Henningsen, 1962, p. 7) probably due largely to mixing with connate waters and exchanges with aquifer rocks. Adjacent to faults, water quality generally declines, possibly due to mixing with saline waters from overlying aquifers, or decreases in permeability with increased exchanges with aquifer rocks. Coarser sands, chiefly at the base of the Hosston Formation, generally have water of higher quality, probably due to effective flushing of connate water, and lesser time-in-contact with aquifer rocks.

In the Waco area, where Hosston water is used generally for domestic and public water supplies, it is within the acceptable range for drinking water (Tables 12, 18) and is used without treatment.

The Hosston waters in the Waco area are used for industrial purposes such as food processing, cooling, and boiler feed.

Wells. In the Waco area the Hosston aquifer is

over-developed (Fig. 21) and further development is undesirable (Figs. 30, 31, 32). The present piezometric surface and projections (Figs. 21, 30, 31) show that there has been a steady decline for many years (Figs. 5, 33), which has increased the danger of contamination by saline water.

Depth of wells. Most Hosston wells have been completed at a depth of 1,500 to 2,500 feet in the Waco area, shallower wells to the west and deeper ones to the east.

Productive capacity of wells. The capacity of wells varies from as little as 50 to more than 1,000 gallons per minute. The average is 500 gallons per minute.

Development of wells. Most Hosston wells in the Waco area range in size from three to 13 $\frac{3}{8}$ inches in diameter. The wells are usually fully cased and slotted (mill or torch) or perforated liners are set opposite producing sands. These methods, although acceptable, are not the most effective. Fine screens, though more expensive in initial installation, keep out the sand and prolong the life of the well considerably (TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975, vol. 1, p. 24).

The Glen Rose Limestone, a source of copious quantities of highly mineralized water, is a potential source of aquifer pollution. This is particularly true when wells penetrating the Glen Rose are not properly cased or when the pressure drops in the Hensel Sand and allows percolation from the Glen Rose into the Hensel. These conditions exist in the Waco area and usually affect domestic and stock wells that traditionally have little or no casing or cement.

Natural contamination along the Balcones fault zone is also apparent (Henningsen, 1961, p. 7), although such contamination is limited to areas in the immediate vicinity of the faults. However, a general deterioration in the chemical quality of the water in the Trinity Group, east of the Balcones fault zone, is apparent.

In areas of large ground-water withdrawals, the decline in artesian pressure and consequent lowering of

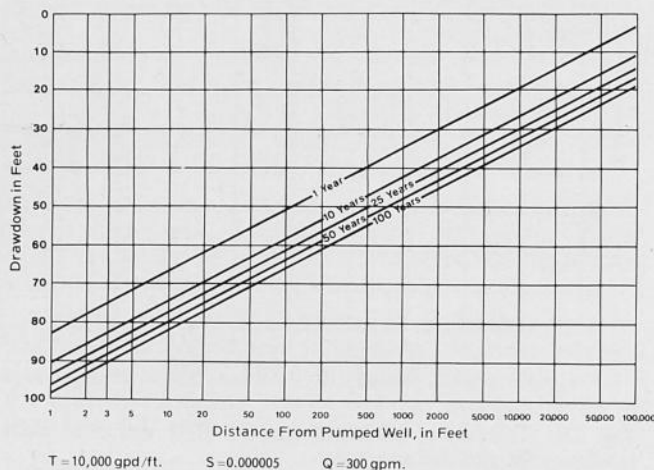


Fig. 28. Relation of decline in water levels to time and distance as a result of pumping from the Hosston Formation under artesian conditions. T=Coefficient of transmissibility in gpd/ft. S=Coefficient of storage. Q=discharge rate in gpm. These data assume an aquifer of infinite areal extent. Adapted from TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975.

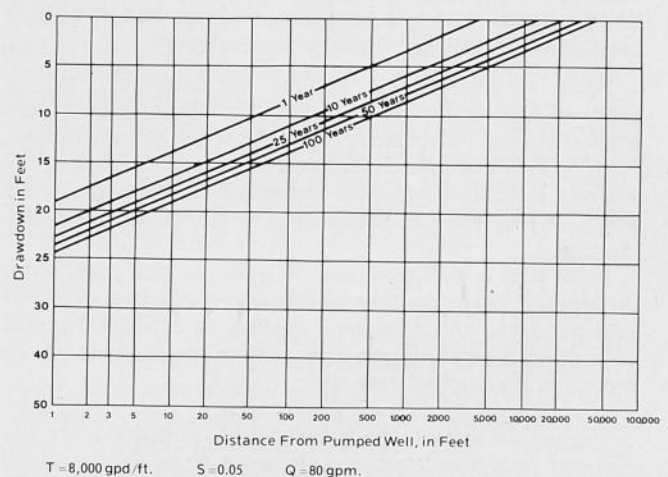


Fig. 29. Relation of decline in water levels to time and distance as a result of pumping from the Hosston Formation under water-table conditions. T=Coefficient of transmissibility in gpd/ft. S=Coefficient of storage. q=discharge rate in gpm. These data assume an aquifer of infinite areal extent. Adapted from TWDB unpub. Trinity aquifer study—Klemm, Perkins, and Alvarez, 1975.

the water table constitute the major problem associated with development. The area where this is most apparent is along Interstate Highway 35, from Temple through Waco and north to Hillsboro. This concentration of public supply and industrial wells has caused a permanent cone of depression to be formed parallel to the highway.

As a result of the water level declines, pumps must be set deeper, larger motors installed, and a higher

pumping lift required, each of which increases the cost of operation. The total water-level decline in the Trinity aquifers from the period from 1900 to 1967 is illustrated in Figure 33. The projected declines from 1967 to 1975 for the Hensel and Hosston Formations are illustrated in Figures 24 and 30. Additional projected water-level declines in the Hensel and Hosston Formations for the period 1967 to 1990 are shown in Figures 25 and 31, and for the period 1967 to 2020 are shown in Figures 26 and 32.

CONCLUSIONS AND RECOMMENDATIONS

1. Flood-plain alluvium in the Waco area is extensively developed. The rate of recharge of the local alluvium is large, and although considerable water is withdrawn from the alluvial flood plain the alluvium readily recharges.

2. In years of low rainfall the water table in the alluvium drops somewhat and caution should be taken that pore space does not collapse and therefore diminish the yield. As a general rule, the years of normal to heavy rainfall offset the dry years and balance out the over-use of dry years. The long-term effects of this see-saw practice may be detrimental and a study should be undertaken to determine optimum yield.

3. In sections where the alluvial ground water is little used, further development is possible. Nevertheless, a program should be instituted based on yearly estimates of rates of recharge, yield, and water quality for wet and dry seasons.

4. To avoid residue buildup in irrigated lands, a program should be established to monitor mineral accumulation and insure proper flushing.

5. Close control of water pumped and well completion methods should be instituted. This program should be designed to protect future availability of ground water. Other sources of potable water should be developed as demands indicate.

6. Human consumption of water from the flood-plain alluvium should be discouraged and an adequate health program begun in areas where this water is used for domestic purposes.

7. Terraces in the Waco area yield water principally in wet seasons, therefore they should not be considered for large demands.

8. Rocks of the Trinity Group, both surface and sub-surface, extend throughout the entire Central Texas region. These are important water-bearing beds and furnish potable water throughout the area. Hensel and Hosston sands are the most important aquifers in the Waco area.

9. The supply of suitable ground water in the Trinity Group is large, but in areas of heavy pumpage the amount of ground water being withdrawn exceeds the natural recharge. Heavy pumpage has caused large water-level declines along the Interstate Highway 35 corridor from Hillsboro through Temple. Further development along this corridor will merely accelerate the decline.

10. Mineralized water of varying quality and quan-

tity is available from the Glen Rose and Edwards Formations.

11. Care should be taken against accidental pollution by heavily mineralized Glen Rose water due to poorly completed wells or seepage into the Hensel sand caused by lowering the hydrostatic pressure of the latter.

12. In order to determine the effects of present and future pumpage, the water-level measurement program should be continued.

13. Additional wells should be properly placed to avoid heavy pumpage areas.

14. To monitor the chemical quality of the water, a program should be instituted to check any possible variation in water quality and movement of contaminated water.

15. In order to improve the quality of data received, periodic collection of water-use information should be continued and expanded. The program should include (a) a collection of power consumption by ground-water irrigators, (b) power and yield tests on certain irrigation wells located in the Waco area (additional power and yield tests are needed in order to more accurately convert the electric power used into gallons of ground water produced), and (c) evaluation of municipal and industrial pumpage.

16. Additional pumping tests should be conducted on wells completed into the Cretaceous aquifers. This program is needed to obtain accurate aquifer characteristics of other principal Cretaceous aquifers.

17. Adequate planning is required to develop and utilize ground water for maximum effectiveness. Development in the future should be based on a program of test drilling, test pumping, and chemical analyses of water from the various producing sands. Such preliminary data can be used to determine the most efficient well completion, optimum pumping rate, efficient pump setting, well spacing, and feasibility of drilling additional wells. (Large concentrated withdrawals of ground water in small areas should be avoided.)

18. The additional investment of a properly screened water well will, in the long run, produce maximum efficiency and economy by increasing the well yield and reducing maintenance costs.

19. The digital computer simulation of the Hensel and Hosston aquifers, the projected values of water-level drawdowns, as well as recharge and aquifer coefficients, should be checked against 1975 measurements. This will establish model accuracy and provide a basis for any needed adjustments.



Fig. 30. Projected water-level decline, Hosston Formation, 1975. Data from TWDB unpub. Trinity aquifer study—Klent, Perkins, and Alvarez, 1975.

Data: Water Development Board Unpublished Trinity Study ● Well location ▲ Projected point
 ● A1 202 alluvial well ● 505 other well
 Contour interval 25 ft.



Fig. 32. Projected water-level decline, Hosston Formation, 2020. Data from TWDB unpub. Trinity aquifer study—Klent, Perkins, and Alvarez, 1975.

Data: Water Development Board Unpublished Trinity Study

- Well location
- ▲ Projected point
- A1 202 alluvial well
- 505 other well

Contour interval 250 ft.



Fig. 33. Water-level decline in wells, Trinity aquifer, 1900-1967. Data from TWDB unpub. Trinity aquifer study—Klent, Perkins, and Alvarez, 1975.

Data: Water Development Board Unpublished Trinity Study ● Well location ▲ Projected point
 ● A1 202 alluvial well
 ● 505 other well Contour interval 50 ft.

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**This TWDB report was published after completion of this manuscript. See Klemm, Perkins, and Alvarez, 1975.

GLOSSARY

ACRE-FOOT (ac-ft). The volume of water required to cover one acre to a depth of one foot (43,560 cubic feet), or 325,851 gallons.

ACRE FEET PER YEAR (ac-ft/yr). One acre-foot per year equals 829.07 gallons per day.

ALKALINITY. Condition caused primarily by the presence of carbonates and bicarbonates, and less frequently by hydroxides, borates, silicates, and phosphates. These components are determined collectively by titration with a standardized solution of a strong acid and are reported as carbonate and bicarbonate.

ALLUVIAL DEPOSITS. See alluvium.

ALLUVIUM. Sediments deposited by streams; includes flood-plain deposits and stream-terrace deposits. Also called alluvial deposits.

AQUIFER. A formation, group of formations, or part of a formation that is water-bearing.

AQUIFER TEST, PUMPING TEST. The test consists of the measurement at specific intervals of the discharge and water level of the well being pumped and the water levels in nearby observation wells. Formulas have been developed to show the relationship among the yield of a well, the shape and extent of the cone of depression, and the properties of the aquifer such as the specific yield, porosity, and coefficients of permeability, transmissibility, and storage.

AQUIFER TEST, RECOVERY TEST. The test consists of the measurement at specific intervals of the water level in the previously pumped well and the observation wells. (See aquifer test, pumping test.) Measurements are begun shortly after the pump is stopped and are continued until the water levels rise (or recover to their positions previous to the start of the test).

ARTESIAN AQUIFER, CONFINED AQUIFER. Artesian (confined) water occurs where an aquifer is overlain by rock of lower permeability (e.g., clay) that confines the water under pressure greater than one atmosphere. The water level in an artesian well will rise above the top of the aquifer. The well may or may not flow.

ARTESIAN WELL. One in which the water level rises above the top of the aquifer whether or not the water flows at the land surface.

BARRIER EFFECT. An impermeable boundary. A hydrological boundary which affects the radial growth of the cone of depression in a pumping well. This occurs after a given elapsed pumping time. Because of this, the drawdown data contained in these pumping tests is abnormal and the transmissibility is less than the true transmissibility.

COEFFICIENT OF STORAGE. It is the rate of water flow in gallons per day through a cross sectional area of one square foot under a unit of hydraulic gradient; the volume of water that an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface.

COEFFICIENT OF TRANSMISSIBILITY. The number of gallons of water that will move in one day through a vertical strip of the aquifer one foot wide and having the height of the aquifer when the hydraulic gradient is unity. It is the product of the field coefficient of permeability and the saturated thickness of the aquifer.

CONE OF DEPRESSION. Depression of the water table of piezometric surface surrounding a discharging well, more or less the shape of an inverted cone.

CONFINING BED. One which because of its position and its impermeability or low permeability relative to that of the aquifer keeps the water in the aquifer under artesian pressure.

CONTAMINATION. An impairment of the quality of the water by sewage (high nitrate content), industrial waste (oil field brines from improperly cased or plugged wells), or intraformational leakage from overlying or underlying undesirable water-bearing units (Glen Rose Formation) to a degree which creates an actual hazard to public health.

DIP OF ROCKS. The angle or amount of slope at which a bed is inclined from the horizontal (e.g., one degree, south-

east; or 90 feet per mile southeast).

DRAINAGE SYSTEM. A surface stream or body of impounded surface water, together with all surface streams and bodies of impounded surface water that are tributary to it.

DRAWDOWN. The lowering of the water table or piezometric surface caused by pumping (or artesian flow). In most instances it is the difference in feet, between the static level and the pumping level.

ELECTRIC LOG. A graph showing the relation of the electrical properties of the rocks and their fluid contents penetrated in a well. The electrical properties are neutral potentials and resistivities to induced electrical currents, some of which are modified by the presence of the drilling mud.

EQUIVALENTS PER MILLION (epm). An expression of the concentration of chemical substances in terms of the reacting values of electrically charged particles, or ions, in solution. One epm of a positively charged ion (e.g., Na⁺) will react with one epm of a negatively charged ion (e.g., Cl⁻). Parts per million are converted to equivalents per million by multiplying by the reciprocal of the combining weight of the ion, as follows:

Cation	Factor	Anion	Factor
Calcium (Ca ⁺⁺)	0.0499	Carbonate (CO ₃ ⁻⁻)	0.0333
Magnesium (Mg ⁺⁺)	.0823	Bicarbonate (HCO ₃ ⁻)	.0164
Sodium (Na ⁺)	.0435	Sulfate (SO ₄ ⁻⁻)	.0208
Potassium (K ⁺)	.0256	Chloride (Cl ⁻)	.0282
		Fluoride (F ⁻)	.0526
		Nitrate (NO ₃ ⁻)	.0161

EVAPOTRANSPIRATION. Water withdrawn by evaporation from a land area, a water surface, moist soil, or the water table, and the water consumed by transpiration of plants.

FACIES. The "aspect" belonging to a geological unit of sedimentation, including mineral composition, type of bedding, fossil content, etc. (e.g., sand facies). Sedimentary facies are areally segregated parts of differing nature belonging to a genetically related body of sedimentary deposits.

FAULT. A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture.

FORMATION. A body of rock that is sufficiently homogeneous or distinctive to be regarded as a mappable unit, usually from a locality where the formation is typical (e.g., Glen Rose Limestone, Paluxy Sand, Georgetown Limestone).

FRESH WATER. Water containing less than 1,000 ppm (parts per million) of dissolved solids.

GROUND WATER. Water in the ground that is in the zone of saturation from which wells, springs, and seeps are supplied.

HARDNESS. Total hardness is the calcium carbonate equivalent of the calcium and magnesium content and sometimes of the iron and aluminum content.

HEAD, OR HYDROSTATIC PRESSURE. Artesian pressure measured at the land surface reported in pounds per square inch or feet of water.

HYDRAULIC GRADIENT. The slope of the water table or piezometric surface, usually in feet per mile.

HYDROLOGIC CYCLE. The complete cycle of phenomena through which water passes, commencing as atmospheric water vapor, passing into liquid or solid form as precipitation, thence along or into the ground, and finally returning to the form of atmospheric water vapor by means of evaporation and transpiration.

IMPERMEABLE. Impervious, having a texture that does not permit water to move through it perceptibly under the head differences ordinarily found in subsurface water.

IRRIGATION. The controlled application of water to arable lands to supply water not satisfied by rainfall.

- LEACHING.** The process of removal of soluble material by passage of water through soil.
- MILLION GALLONS PER DAY (mgd).** One mgd equals 3.068883 acre-feet per day or 1,120.91 acre-feet per year.
- MINERAL.** Any chemical element or compound occurring naturally as a product of inorganic processes.
- OUTCROP.** That part of a rock layer which appears at the land surface.
- PARTS PER MILLION (ppm-weight).** One part per million represents one milligram of solute in one kilogram of solution. As commonly measured and used, parts per million is numerically equivalent to milligrams of a substance per liter of water.
- PERCENT SODIUM.** A ratio, expressed in percentage, of sodium to the sum of the positively charged ions (calcium, magnesium, sodium, and potassium), all ions in equivalents per million.
- PERCOLATION.** The movement, under hydrostatic pressure, of water through the interstices of a rock or soil, except the movement through large openings such as caves.
- PERMEABLE.** Pervious, having a texture that permits water to move through it perceptibly under the head differences ordinarily found in subsurface water. A permeable rock has communicating interstices of capillary or supercapillary size.
- PERMEABILITY OF AN AQUIFER.** The capacity of an aquifer for transmitting water under pressure.
- PIEZOMETRIC SURFACE.** An imaginary surface that everywhere coincides with the static level of the water in the aquifer. The surface to which the water from a given aquifer will rise under its full head.
- POROSITY.** The ratio of the aggregate volume of interstices (openings) in a rock or soil to its total volume, usually stated as a percentage.
- RECHARGE OF GROUND WATER.** The process by which water is absorbed and is added to the zone of saturation, also used to designate the quantity of water that is added to the zone of saturation, usually given in acre-feet per year or in million gallons per day.
- RECHARGE, REJECT.** The natural discharge of ground water in the recharge area of an aquifer by springs, seeps, and evapotranspiration, which occurs when the rate of recharge exceeds the rate of transmission in the aquifer.
- RESIDUAL SODIUM CARBONATE (Eaton, 1950).** The amount of carbonate plus bicarbonate, expressed in equivalents per million, that would remain in solution if all the calcium and magnesium were precipitated as the carbonate. Residual sodium carbonate equals $(\text{CO}_3^{--} + \text{HCO}_3^-) - \text{Ca}^{++} + \text{Mg}^{++}$.
- RESISTIVITY (electrical log).** The resistance of the rocks and their fluid contents penetrated in a well to induced electrical currents. Permeable rocks containing fresh water have high resistivities.
- SAFE YIELD.** The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible. The practical rate of withdrawing water from an underground reservoir perennially for human use.
- SALINITY OF WATER.** From a general classification of water based on dissolved-solids content by Winslow and Kister (1956, p. 5): Fresh water, less than 1,000 ppm; slightly saline water, 1,000 to 3,000 ppm; moderately saline water, 3,000 to 10,000 ppm; very saline water, 10,000 to 35,000

ppm; and brine, more than 35,000 ppm.

SODIUM-ADSORPTION RATIO (SAR). The ratio is related to the adsorption of sodium by the soil and is an index of the sodium, or alkali, hazard of the water. Concentrations of

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

constituents are in equivalents per million.

SPECIFIC CAPACITY. The rate of yield of a well per unit of drawdown, usually expressed as gallons per minute per foot of drawdown. If the yield is 250 gpm and the drawdown is 10 feet, the specific capacity is 25 gpm/ft.

SPECIFIC CONDUCTANCE. A measure of the ability of a water to conduct an electrical current, expressed in micromhs at 25° C. Being related to the number and specific chemical types of ions in solution, the specific conductance can be used for approximating the salinity of the water. The following general relations are applicable:

$$\text{Specific conductance} \times 0.65 = \text{ppm dissolved solids.}$$

$$\frac{\text{Specific conductance}}{100} = \frac{\text{total epm}}{2}$$

SPECIFIC YIELD. The quantity of water that an aquifer will yield by gravity if it is first saturated and then allowed to drain; the ratio expressed in percentage of the volume of water drained to volume of the aquifer that is drained.

STORAGE. The volume of water in an aquifer, usually given in acre-feet.

TRANSPIRATION. The process by which water vapor escapes from a living plant, principally the leaves, and enters the atmosphere.

WATER LEVEL. Depth to water, in feet below the land surface, where the water occurs under water-table conditions (or depth to the top of the zone of saturation). Under artesian conditions the water level is a measure of the pressure on the aquifer, and the water level may be at, below, or above the land surface.

WATER LEVEL, PUMPING. The water level during pumping measured in feet below the land surface.

WATER LEVEL, STATIC. The water level in an unpumped or nonflowing well, measured in feet above or below the land surface or sea-level datum.

WATER TABLE. The upper surface of a zone of saturation except where the surface is formed by an impermeable body of rock.

WATER-TABLE AQUIFER, UNCONFINED AQUIFER. An aquifer in which the water is unconfined; the upper surface of the zone of saturation is under atmospheric pressure only and the water is free to rise or fall in response to the changes in the volume of water in storage. A well penetrating an aquifer under water-table conditions becomes filled with water to the level of the water table.

WEIGHTED AVERAGE. Represents approximately the chemical character of the water if all the water passing a point in the stream during the year were impounded and mixed in a reservoir. Weighted average is calculated by dividing the sum of the products of water discharge and concentration of individual analyses by the sum of the water discharged for the period that the analyses represent.

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