Report 235

OCCURRENCE, AVAILABILITY, AND CHEMICAL QUALITY OF GROUND WATER IN THE EDWARDS PLATEAU REGION OF TEXAS

TEXAS DEPARTMENT OF WATER RESOURCES

July 1979

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By

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OCCURRENCE, AVAILABILITY, AND CHEMICAL QUALITY OF GROUND WATER IN THE EDWARDS PLATEAU REGION OF TEXAS

ABSTRACT

The Edwards Plateau is located in southwest Texas and lies between 98º and 103º west longitude and 29º and 32º north latitude. The area composes approximately 23,000 square miles and includes all or parts of 28 counties. The region is bounded on the west by the Pecos River; on the north, northwest, and northeast by the physical limit of the Cretaceous rocks; on the east by the Llano uplift; on the south and southeast by the Balcones fault system; and on the southwest by the Rio Grande.

The agricultural economy of the region is based primarily on ranching. Some of the leading sheep- and goat-producing counties in the State are in the Edwards Plateau region. In 1972, the agricultural income was over $135 million.

The production of oil and gas is the principal industry, especially in the northwestern part of the region. More than three billion barrels of oil have been produced in the study area since oil was first discovered in the area in 1925.

Rocks of sedimentary origin overlie the Precambrian granites beneath the Edwards Plateau. These sedimentary rocks range in thickness from a few hundred feet along the eastern part of the Plateau to about 15,000 feet in the western part.

The principal aquifers, or water-bearing units, in order of importance and development are the Edwards-Trinity (Plateau), composed of the Antlers Formation and the Edwards and associated limestones; the alluvium; the lower Cretaceous, composed of the Hosston, Sligo, Pearsall, and Glen Rose Formations; the Hickory; and the Ellenburger-San Saba. Other units that yield fresh to slightly saline water in limited areas on or near the Edwards Plateau are the Ogallala aquifer and rocks of Pennsylvanian, Permian, and Triassic age.

The total amount of fresh to slightly saline ground water available from all aquifers on the Edwards Plateau is more than 450,000 acre-feet per year. Of this amount, approximately 308,000 acre-feet is available annually from the Edwards-Trinity (Plateau) and the alluvium aquifers.

In 1972 approximately 86,000 acre-feet of ground water was pumped by wells on the Edwards Plateau for municipal, industrial, irrigation, livestock, and domestic use. About 70 percent of the water pumped was for irrigation. Water levels are declining in the Edwards-Trinity (Plateau) aquifer in areas of heavy pumping in Ector, Glasscock, Midland, Reagan, and Upton Counties. The greatest water-level declines are in southern Glasscock and northern Reagan Counties.

Ground water in most of the counties on the Edwards Plateau is suitable for municipal, industrial, and agricultural uses. The water is generally very hard, but treatment methods can be used to remove calcium carbonate. Other undesirable dissolved minerals such as sulfate, chloride, and fluoride are present in varying amounts in water from the Antlers Formation; however, the water has been used for most purposes without apparent harmful results.

The prospect of irrigation from the Edwards-Trinity (Plateau) aquifer is good, especially in the central part of the Plateau where the topography is relatively flat, the soil is deep, and the growing season is long.

OCCURRENCE, AVAILABILITY, AND CHEMICAL QUALITY OF GROUND WATER IN THE EDWARDS PLATEAU REGION OF TEXAS

INTRODUCTION

Purpose and Scope

Field work for the Edwards Plateau region study was begun in the summer of 1965 to collect and compile ground-water information for testimony to be presented at a public hearing of the Texas Water Rights Commission concerning the existence and extent of an underground water reservoir. Following that hearing, the data-gathering effort was expanded to establish a better understanding of the geologic and hydrologic characteristics of the Edwards-Trinity (Plateau) aquifer and to prepare a report useful to landowners, the Texas Water Development Board, other state and federal agencies, and the general public.

The scope of the study included the collection and compilation of all available data pertaining to the occurrence, availability, and chemical quality of water in the Edwards-Trinity (Plateau) aquifer and other aquifers on the Edwards Plateau.

Location and Extent of the Region

The Edwards Plateau is located in southwest Texas between 98° and 103° west longitude and 29° and 32° north latitude. The area of this report corresponds primarily to the extent of the Edwards-Trinity (Plateau) aquifer (Figure 1). It covers approximately 23,000 square miles and includes all or parts of 28 counties. The region is bounded on the west by the Pecos River; on the north, northwest, and northeast by the physical limit of the Cretaceous rocks; on the east by the Llano uplift; on the south and southeast by the Balcones fault system; and on the southwest by the Rio Grande.

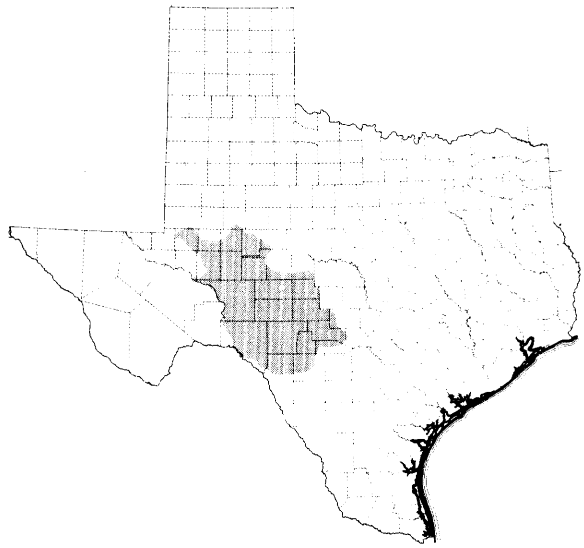


Figure 1.—Location of the Edwards-Trinity (Plateau) Aquifer

Methods of Investigation

The study of the ground-water resources of the Edwards Plateau was accomplished by performing the following tasks:

1. Irrigation, public supply, industrial, and selected domestic and livestock wells were inventoried (a total of 5,128 wells). Records of wells and springs are included in the tables or in referenced reports. Locations of wells and springs are shown on county well location maps in this report or in referenced reports. Surface elevations of these wells and springs were determined from topographic maps, by Paulin altimeter, and by surface-elevation maps of seismic projects furnished by oil companies.

2. A geologic map was compiled to show the surface formations on the Edwards Plateau.

3. Maps were constructed to show the altitude of the top of Trinity Group, altitude of the base of the Edwards-Trinity (Plateau) aquifer, altitude of water levels in the Edwards-Trinity (Plateau) aquifer, and the area of greatest water-level decline.

4. Chemical analyses of water samples were obtained and compiled to determine the chemical quality of the ground water.

5. A total of 940 electric and gamma-ray logs of oil and gas tests were used to determine the top and base of Cretaceous formations, and to show their relationship to the underlying rocks.

6. Compilations were made of all available data on present and past pumpage of ground water for irrigation use and public supply, and ground water pumpage for domestic and livestock was estimated by using U.S. Department of Commerce census and U.S. Department of Agriculture animal population in the region.

7. Precipitation, evaporation, transpiration, and temperature data were compiled to assist in estimating recharge to aquifers, base flow of streams, and ground-water pumpage.

8. Data were compiled and maps were constructed to show location and amounts of reported brine production and location of brine disposal wells for the years 1961 and 1967.

9. Various graphs, charts, tables, and geologic sections were constructed to illustrate geohydrologic conditions.

10. Pumping tests of wells were conducted, or results of pumping tests were collected from files, and the volume of dewatering in the Antlers Formation was calculated to determine the hydrologic characteristics of the water-bearing rocks.

11. Hydrographs of observation wells were constructed to determine the annual and long-term fluctuations of water levels.

12. Available hydrologic data were studied to determine quantity and quality of ground water available for future development.

13. Prior to the completion of this study, basic data reports were published on Glasscock, Irion, Reagan, Schleicher, Sterling, and Sutton Counties in order to make data on water wells and the chemical quality of the ground water readily available for use. These data were used, but not reproduced, in the present study.

Previous Investigations

Collection of basic ground-water data on 11 counties on the Edwards Plateau was conducted during the period 1936 to 1942. Duplicated reports of records of wells, drillers' logs, water analyses, and maps showing locations of wells and springs in these counties are as follows: Ector County, Davis (1937); Edwards County, Frazier (1939); Gillespie County, Shields (1937); Glasscock County, Lang (1937); Howard County, Samuell (1937); Irion County, Frazier (1941); Kinney County, Bennett and Cromack (1940); Midland County, Davis (1938); Sterling County, George and Dalgarn (1942); Tom Green County, Barnes and Dalgarn (1941); and Val Verde County, Frazier (1940).

Follett (1956) compiled records of water-level measurements in observation wells in Kinney, Uvalde, and Val Verde Counties, 1929 to March 1956. Currently, water levels in nine wells in Val Verde County are being measured at annual intervals as a part of the Texas Water Development Board observation-well program.

Rayner (1959a, 1959b, 1959c) compiled records of water-level measurements in observation wells in Crockett, Glasscock, Midland, Reagan, Sterling, Tom Green, and Upton Counties, 1937 through 1957. Currently, water levels in 13 wells in Crockett County, 18 wells in Glasscock County, 11 wells in Reagan County, and four wells in Sterling County are being measured at annual or bimonthly intervals as a part of the Board observation-well program.

Detailed ground-water studies have been conducted in the following counties on the Edwards Plateau: Coke County, Wilson (1973); Crockett County, Iglehart (1967); Ector County, Knowles (1952); Edwards County, Long (1962); Kerr County, Reeves (1969); Kimble County, Alexander and Patman (1969); Kinney County, Bennett and Sayre (1962); Menard County, Baker and others (1965); Tom Green County, Willis (1954); Upton County, White (1968); Uvalde County, Welder and Reeves (1962); and Val Verde County, Reeves and Small (1973).

Reconnaissance investigation of the ground-water resources of the Colorado River basin was conducted by Mount and others (1967) during 1959 to 1961. Reconnaissance investigation of the ground-water resources of the Middle Rio Grande basin was conducted by Brown, Rogers, and Baker (1965) during 1959 to 1961.

Basic ground-water data reports of six counties on the Edwards Plateau have been conducted as follows: Schleicher County, Muller and Couch (1971); Glasscock

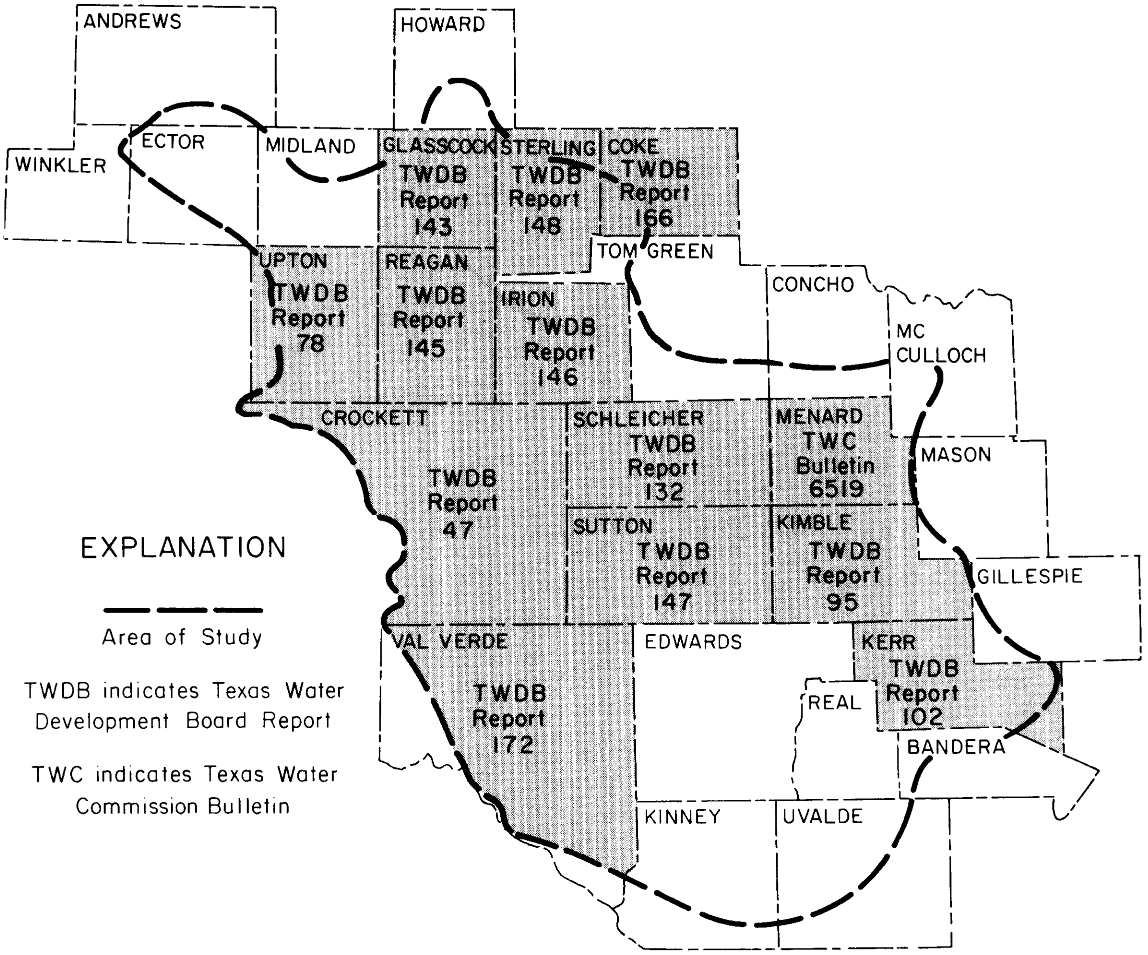


Figure 2.—Previously Published Reports Containing Ground-Water Data Used in This Study

County, Couch and Muller (1972); Reagan County, Muller and Couch (1972); Irion County, Pool (1972); Sutton County, Muller and Pool (1972); and Sterling County, Pool (1972).

Previously published reports that contain data used in this study are shown on Figure 2.

Well-Numbering System

The well-numbering system used in this report, based on the divisions of latitude and longitude, is the one adopted by the Texas Water Development Board for use throughout the State (Figure 3). In this system, each well is assigned a seven-digit number and a 2-letter county designation prefix. Each 1-degree quadrangle in or overlapping into the State is given a two-digit number from 01 to 89. These are the first two digits of a well number. Each 1-degree quadrangle is further divided into sixty-four 7½-minute quadrangles which are each assigned a two-digit number from 01 to 64 constituting the third and fourth digits of a well number. Finally, each 7½-minute quadrangle is subdivided into nine 2½-minute quadrangles which are numbered 1 to 9 (fifth digit). Within these 2½-minute quadrangles, each well is assigned a two-digit number beginning with 01 (the last two digits).

The Edwards Plateau region is in 1-degree quadrangles 27, 28, 29, 42, 43, 44, 45, 53, 54, 55, 56, 57, 68, 69, 70, and 71. The 1-degree and 7½-minute quadrangles are shown on the well-location maps. For reasons of space, the 2½-minute quadrangles are not shown. Their notation, however, occurs as the first digit of the 3-digit number beside each well location.

In this report, each county has a two-letter prefix to identify the county in which the well is located. The letter prefixes are as follows:

Andrews	AB	Coke	DR
Bandera	AS	Concho	DZ

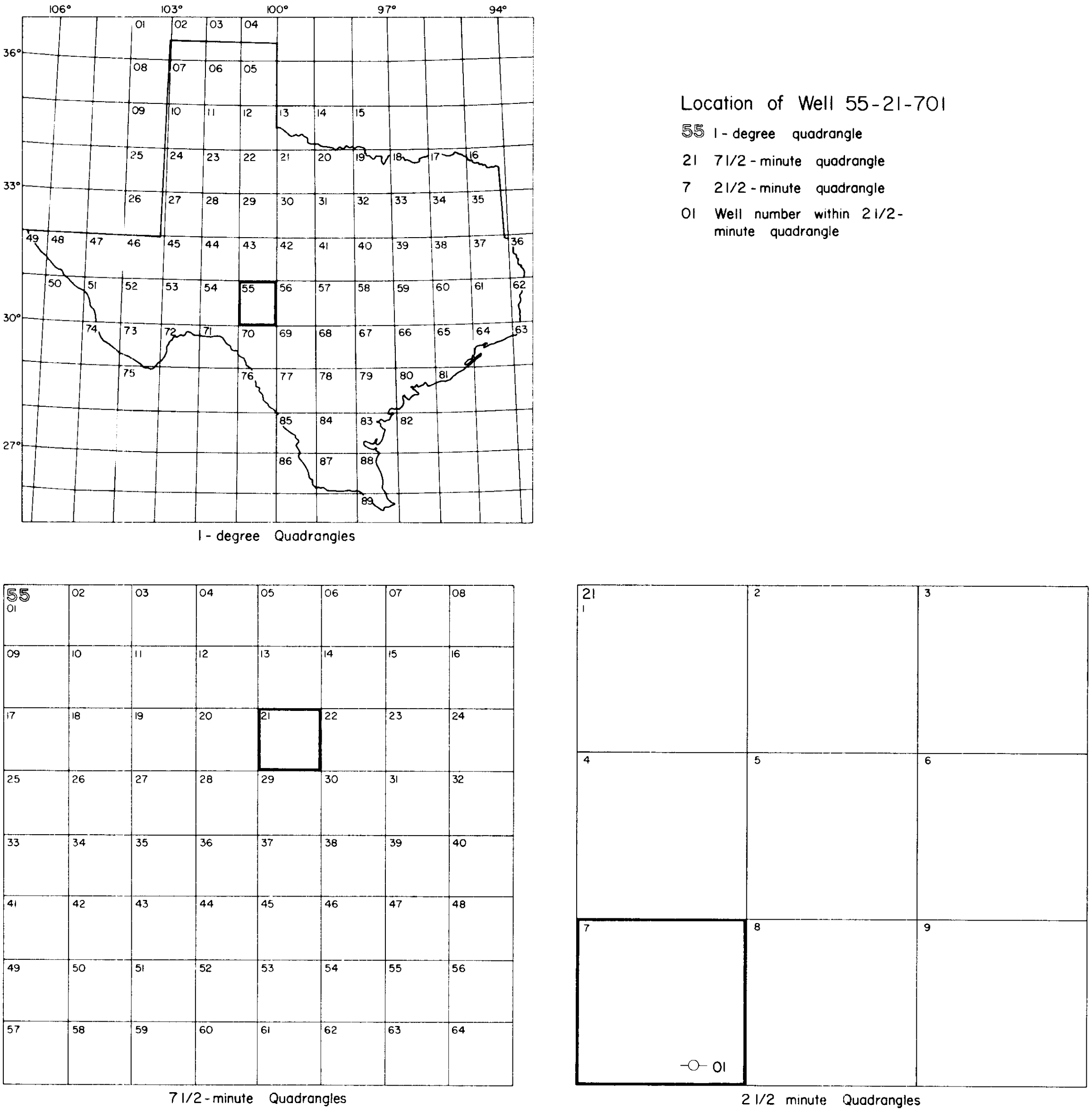


Figure 3.—Well-Numbering System

Crockett	HJ	Kimble	RK	Schleicher	WY	Upton	YL
Ector	JH	Kinney	RP	Sterling	XP	Uvalde	YP
Edwards	JJ	McCulloch	SS	Sutton	XS	Val Verde	YR
Gillespie	KK	Mason	SZ	Tom Green	YB	Winkler	ZP
Glasscock	KL	Menard	TH				
Howard	PB	Midland	TJ				
Irion	PK	Reagan	UZ				
Kerr	RJ	Real	WA				

Acknowledgements

This study was greatly facilitated by the aid and cooperation of many individuals, oil companies, and organizations. Appreciation is expressed to the well drillers, officials of municipalities, industries, utility

companies, and water-well owners for permission to inventory wells. Special acknowledgement is made to the U.S. Soil Conservation Service for supplying ownership data and to the U.S. Geological Survey for data furnished from their files.

Personnel

The author is indebted to Glenward Elder, Daniel Muller, and James Pool for writing the first draft of parts of this report. Basic field data for this report were collected by the following personnel:

Name	Year started on project
H. E. "Gene" Couch	1965
Danney Corley	1969
Glenward Elder	1969
Kenneth Jackson	1968
Daniel Muller	1965
James Pool	1967
Richard Preston	1966
Robert Price	1966

Topography, Drainage, and Vegetation

The topography of the Edwards Plateau region ranges from rolling plains to flat tableland and rugged, steep-walled canyons and draws. The altitude of the land surface ranges from about 1,000 feet in Uvalde County to 3,300 feet in Ector County.

The surface in the northern part of Ector, Midland, Howard, and Glasscock Counties (the southern limit of the High Plains) is covered by Ogallala sediments of Tertiary age. This surface merges with the northern limit of Cretaceous rocks of the Plateau as rolling plains which have been altered slightly by stream erosion. In the southwest part of Ector and Upton Counties, the Cretaceous rocks, have been removed by erosion which resulted in a northwest-southeast trending escarpment known as Concho Bluff. The principal vegetation in this area consists of short grasses, mesquite, cactus, creosotebush, and scattered shin oak.

The limit of the Edwards Plateau region on the east and northeast is a result of erosion by the Colorado River and its tributaries. The North Concho River has dissected the Cretaceous rocks in northeast Glasscock, northern Sterling, and Tom Green Counties. Erosion by other tributaries of the Colorado River removed the Cretaceous rocks in parts of Concho, McCulloch, Menard, Kimble, and Gillespie Counties. The surface relief in these counties is greater than the surface relief in the northwest due to erosion of the softer rocks of Triassic, Permian, and Pennsylvanian ages. Grasses, mesquite, live oak, and scattered stands of juniper (cedar) are predominant in this area.

The central part of the Plateau which includes parts of Concho, Irion, Edwards, Kinney, and Menard Counties, is relatively flat and featureless except for erosion along drainage courses and occasional sink holes formed by solution of the limestone bedrock. Principal vegetation here consists of grasses, live oak, shin oak, juniper (cedar), mesquite, and cactus.

The greatest topographic relief is in the southern and southwestern parts of the Plateau where streams have cut through the resistant limestones. Steep-walled canyons and draws of moderate to considerable relief are present in Bandera, Crockett, Edwards, Gillespie, Kerr, Kimble, Kinney, Real, Uvalde, and Val Verde Counties. Vegetative cover in this area consists mainly of short grasses, juniper (cedar), live oak, mesquite, cactus, and guajillo.

About 75 percent of the study area is drained by the Colorado River and its major tributaries, the Concho, San Saba, and Llano Rivers. About 20 percent of the area is drained by the Devils and Pecos Rivers and about 5 percent is drained by the Frio, Guadalupe, Medina, Nueces, and Sabinal Rivers.

Climate

The climate of the Edwards Plateau region ranges from semiarid in the northwest to subhumid in the southeast. The seasons are characterized by hot summers and mild winters. The July maximum temperature ranges from 94°F (34°C) in Sutton County to 98°F (37°C) in Tom Green County. The January minimum temperature ranges from 30°F (-1°C) in Howard County to 40°F (4°C) in Val Verde County. The first frost in autumn occurs about November 6 in Ector, Howard, and Midland Counties, and the last frost in spring usually occurs about April 3. The first frost generally occurs about December 9 in Val Verde County and the last frost occurs about March 10. The frost-free days (growing season) varies from 213 days in Kimble County to 300 days in Val Verde County.

The mean annual precipitation ranges from 12 inches in western Ector County in the northwest to 32 inches in Bandera and Gillespie Counties in the southeast. Figure 4 shows the average annual precipitation for the region for the period 1931-60, and the average monthly precipitation for the period of record at selected stations on the Plateau.

Evaporation rates are generally high throughout the Plateau because of high temperature, low humidity and precipitation, and prevailing winds. Table 1 shows the computed annual gross and net lake surface evaporation by county in the study area for the period 1940 through 1965. The annual average net lake surface evaporation for the period 1940-65 ranges from 43 inches in Gillespie County to 69 inches in Ector County. Net lake surface evaporation is the actual evaporation loss which would occur; that is, the gross lake surface evaporation less the effective rainfall.

History, Population, and Economy

Fifteen of the 28 counties on the Edwards Plateau were organized from Bexar County, or the Bexar District; nine were organized from the original Tom Green County; and three were organized from the original Crockett County. The first county to be organized was Gillespie County in 1848 and the last to be organized was Real County in 1913.

The Edwards Plateau is a sparsely populated area averaging about 12 persons per square mile. The 1970 estimated population of the 28 counties comprising the study area was 416,847. Population of the major trade centers was as follows: Big Spring 28,735; Del Rio 21,330; Midland 59,463; Odessa 78,380; and San Angelo 63,884. Many smaller towns and communities on the Plateau serve as local markets, supply centers, and seats of local and county government. The region is served by two railroads and by an excellent network of State and federal highways.

The total income for the study area in 1968 was $1.1 billion, with agricultural income representing $100 million of the total. The agricultural economy of the Edwards Plateau region is primarily ranching, and the region includes some of the leading sheep and goat producing counties in the State. There were over 4 million head of livestock (sheep, cattle, goats, and horses) in the study area in 1968. Sheep is the leading livestock in 68 percent of the counties; cattle the leading livestock in 28 percent of the counties; and goats and horses make up the remaining 4 percent. Poultry raising is expanding in the region due to available markets. Farming is spotted throughout the region with crops consisting of small grains, hay, cotton, peanuts, vegetables, pecans, and fruits.

The production of oil and gas is also important to the economy. Fifteen of the 28 counties on the Edwards Plateau are presently producing oil and gas. Over 3 billion barrels of oil has been produced since 1925 when oil was first discovered in the region. Current (1969) casinghead gas production is over 3 billion cubic feet per year.

Table 1.—Average Annual Lake-Surface Evaporation, 1940-65

(From Kane, 1967)

County	Gross evaporation (inches)	Net evaporation (inches)	County	Gross evaporation (inches)	Net evaporation (inches)
Coke	85	63	McCulloch	75	51
Concho	79	58	Menard	78	57
Crockett	83	67	Midland	82	68
Ector	82	69	Reagan	83	68
Edwards	76	55	Real	74	52
Gillespie	69	43	Schleicher	82	66
Glasscock	82	67	Sterling	82	65
Howard	81	64	Sutton	78	59
Irion	83	66	Tom Green	83	66
Kerr	73	49	Upton	83	66
Kimble	74	52	Uvalde	74	52
Kinney	77	57	Val Verde	84	67

GEOLOGY

Geologic History and Regional Structure

Precambrian Period

During the middle Precambrian Period, pre-existing rocks were altered by metamorphism (heat and compressive forces). These metamorphic rocks occur at the surface in the Llano uplift, and rocks of similar alteration occur beneath the Edwards Plateau. Following the alteration of the rocks, two series of granites were intruded in the Llano area. The Llano uplift and other major structural features of the Edwards Plateau are shown on Figure 5.

Extensive erosion began in late Precambrian time and possibly continued into the early Cambrian. The known topographic relief of the terrain resulting from the erosion in the Llano area exceeded 800 feet.

Also, during late Precambrian time, a low arch was forming in the Plateau area from Sutton County on the south to Nolan County on the north. The term *West Central Texas upwarp* has been applied to this structural feature.

Cambrian Period

The sea advanced into the central Texas area during late Cambrian time and deposition of sediments began which continued into early Ordovician. These sediments were deposited in an apparent trough through Menard and McCulloch Counties and as far north as Callahan County. Deposition of sediments to the northwest of this trough was affected, either by thinning or missing due to onlap over the regionally high West

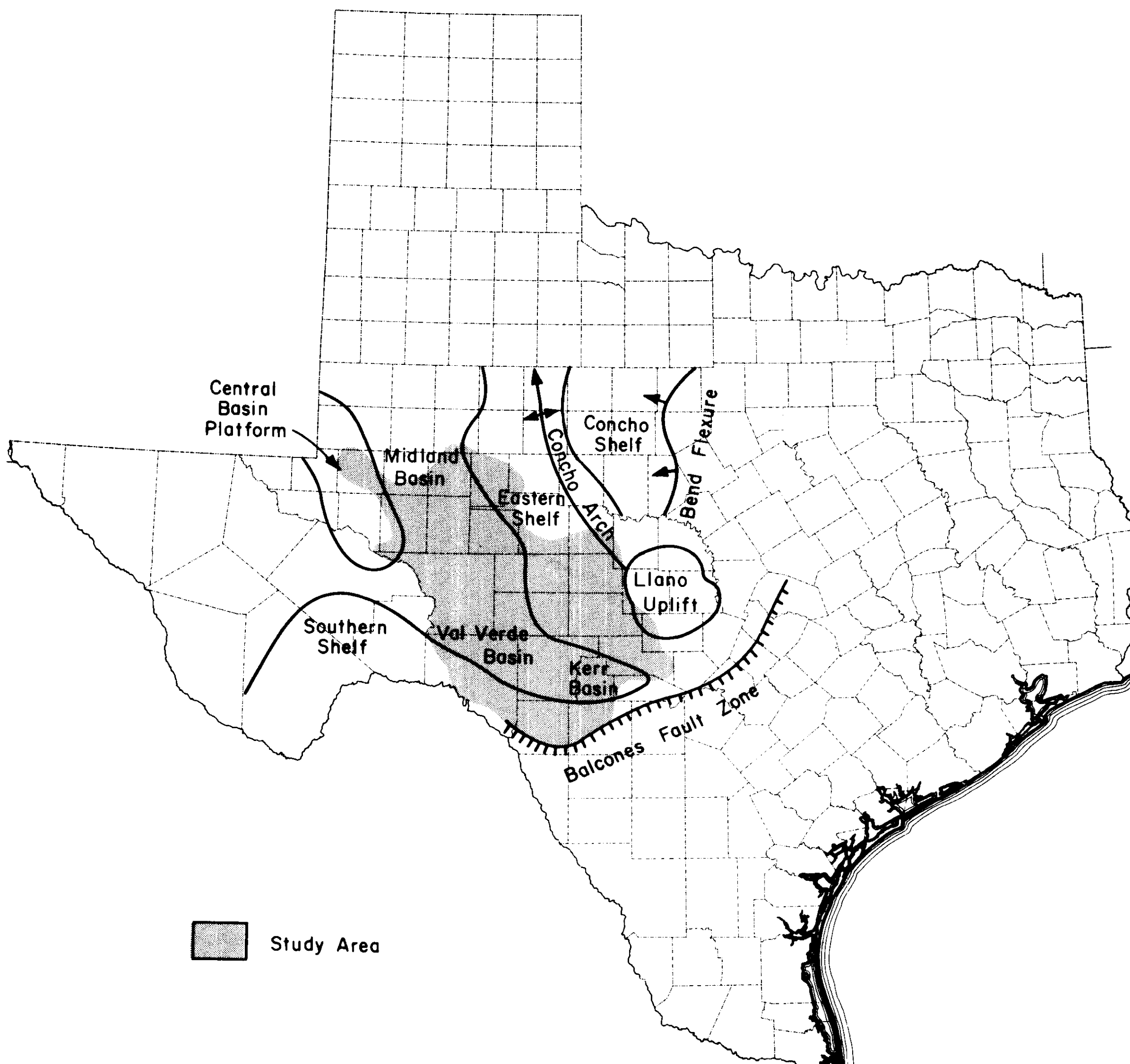


Figure 5.—Structural Features of West-Central Texas

Central Texas upwarp. Differential subsidence (uneven sinking of the sea bottom) continued through the Cambrian.

Rocks of the Cambrian dip to the west and northwest at about 120 feet per mile from the outcrop in southeastern McCulloch County. From the outcrop in the central part of Mason County, the dip is to the southwest at 100 to 150 feet per mile.

Ordovician Period

During early Ordovician time, an extensive epicontinental sea covered Texas resulting in deposition of the Ellenburger Group. In middle Ordovician, uplift and erosion in the Edwards Plateau region and northward not only removed previously deposited sediments but restricted succeeding deposition. This uplift, termed *the Texas peninsula* apparently extended from Uvalde and Medina Counties on the south to the Red River on the north.

In late Ordovician time, the Llano area again subsided and deposition occurred. The close of the Ordovician experienced renewed uplift and erosion.

Pennsylvanian Period

The structural history of the Pennsylvanian Period is a series of land emergence and erosion followed by submergence and deposition. Extensive earth movements (folding and faulting) during the period also affected pre-existing structure and sedimentation.

During early Pennsylvanian, a broad foreland developed in the area of Kimble, Menard, Concho, McCulloch, and Tom Green Counties and counties to the north. Following erosion of this foreland, limestone was deposited. Also, near the end of early Pennsylvanian time, the Concho arch, an elongated domal structure, was uplifted. This arch extended from Mason County on the south to Dickens County on the north.

Development of the Concho shelf, Bend flexure, and the Eastern shelf began during middle Pennsylvanian time. Also, during middle Pennsylvanian, uplift and faulting occurred near the present towns of Richland Springs, Bend, Pontotoc, San Saba, and Lampasas. This had a major effect on Cambrian and Ordovician sediments.

Uplift of the western Llano area during late Pennsylvanian time removed much of the sediments deposited earlier. In parts of Mason, McCulloch, and Menard Counties, late Pennsylvanian sediments may rest on rocks of Precambrian age. The Llano area again experienced uplift caused by the initial westward tilting toward the Midland basin. This tilting continued through the Permian and Triassic Periods. Alternate advance and retreat of shorelines near the end of the Pennsylvanian produced sand, limestone, and shale beds on the Concho shelf. Farther west, on the Eastern shelf, reef masses were formed. The dip of the Pennsylvanian sediments is to the west-northwest.

Permian Period

Little regional earth movement was experienced during early Permian, except for the continued tilting of the landmass toward the Midland basin. This movement caused the shoreline to migrate westward. Relatively unstable near-shore conditions existed along the eastern part of the platform area, while reef masses were building on the Eastern shelf in Coke, Tom Green, and Schleicher Counties.

Some reef building continued into middle Permian time on the Eastern shelf; however, the predominant sediments were gypsum, anhydrite, and dolomitic limestone. During the middle Permian, sediments continued to thicken westward toward the basin area.

Conditions favorable to the deposition of evaporites continued throughout late Permian time with salt, anhydrite, and shale (red beds) being deposited in the basin area. To the east, along the western edge of the Eastern shelf, evaporites gave way to sands and shales with minor amounts of anhydrite. The dip of the Permian is to the west-northwest into the Midland basin.

Triassic Period

As the Permian sea retreated from the Midland basin, erosion and local folding followed; thus, separating the Permian formations from subsequent sediments by an extensive regional unconformity. Although erosion was widespread, the amount of Permian material removed is thought not to have been great.

In late Triassic time, considerable uplift to the east initiated deposition of sands, conglomerates, and shales west of Tom Green, Coke, Irion, and Crockett Counties. The Triassic sediments were deposited on the eroded Permian surface.

Cretaceous Period

Triassic and Paleozoic rocks were subjected to erosion during the Jurassic and early Cretaceous, forming a nearly flat or broadly undulating plain which Hill (1932, p. 260) named the Wichita paleoplain. It was over this eroded surface that the last epicontinental sea advanced northward from the Gulf across Texas.

Two structural features in this area are worthy of special note. The first is an area in southern Reagan County, composed of two subsurface depressions-one to the west of Big Lake and the other northeast of Big Lake. These depressions apparently were caused by solution of Permian evaporites and collapse of overlying sediments. These depressions were later filled with collapse debris and subsequent sediments.

The other major structural feature is a “high” located at the common corners of Schleicher, Menard, Kimble, and Sutton Counties. According to Cartwright (1932, p. 694), this “high” was an island of Permian sediments in the Trinity sea.

During most of Cretaceous time, the sea advanced inland. The sea then began retreating by stages of advance and retreat. A number of interruptions occurred in the sedimentation cycle during the Cretaceous, the most prominent being the erosional unconformity between the Comanche and Gulf Series.

Major faulting of the Cretaceous rocks is generally confined to the Balcones fault zone south of the Edwards Plateau. This fault zone extends across Kinney, Uvalde, and Medina Counties, curving northward through Bexar, Comal, Hays, Travis, Williamson, Bell, and McLennan Counties. The fault zone forms a hinge line between the Gulf Coastal Plain and the higher Edwards Plateau area. The faulting is thought to have begun in the late Cretaceous and continued into the Cenozoic. As the sediment load increased in the Gulf of Mexico and Gulf Coastal Plain, structural adjustment in the form of normal gravity faults resulted in the Balcones fault zone.

The general dip of the Cretaceous beds is to the southeast about 10 feet per mile with the angle of dip increasing near the Balcones fault zone.

Quaternary Period

With the Edwards Plateau above sea level, erosion attacked the thick sections of Cretaceous rocks, depositing alluvium along the streams which traverse the Plateau. The alluvium is in the form of terraces and flood-plain deposits that are Pleistocene and Recent in age.

No major post-Cretaceous structural changes have occurred within the Edwards Plateau except perhaps near the southern boundary in association with the Balcones faulting. Minor folding and faulting has occurred as well as the development of joint systems, solution channels, and caverns in the limestones.

Stratigraphy

The geologic units within the Edwards Plateau, which contain fresh to slightly saline water (less than 3,000 milligrams per liter dissolved solids), range in age from Cambrian to Recent. The surface exposures of the geologic units within the study area are illustrated in Figure 6, and the thickness, lithology, and water-bearing characteristics of these units are summarized in Table 2. The following discussions pertain primarily to those units that contain fresh to slightly saline water.

Cambrian

The Hickory Sandstone Member of the Riley Formation was deposited upon an unevenly eroded surface of metamorphic and igneous rocks of Precambrian age and thus varies in thickness. This variation in thickness is not only due to depositional environment but also to subsequent erosion and faulting. The thickness of the Hickory is reported to be 320 feet in Gillespie County and 500 feet in Kimble County. On the outcrop in southeastern McCulloch County, the thickness is approximately 360 feet with an average of 400 feet to the west and northwest towards Menard and Concho Counties. Figure 7 shows the outcrop and the altitude of the base of the Hickory.

Near the outcrop, the Hickory is overlain by the Cap Mountain Limestone Member of the Riley Formation; the contact between these two members is placed at a topographical and vegetational break. The gentle, sandy slopes of the Hickory supports the growth of deciduous trees, whereas the steeper, more resistant slopes of the Cap Mountain are more compatible to the growth of cedar. In the subsurface, the contact is not as readily distinguished.

Normally, the Hickory is non-calcareous and non-glauconitic in contrast to some of the younger Cambrian sandstones. It is composed mainly of yellow, brown, and red, angular to subround, cross-bedded sandstone cemented with iron oxide or clay, with numerous shale beds in the upper part of the section.

The sandstone varies from very fine grained to coarse grained with the latter being more predominant in the lower part; locally conglomerate is present at the base of the Hickory.

The San *Saba Limestone Member of the Wilberns Formation* is predominantly glauconitic limestone with sandstone and dolomite beds. However, notable facies changes do occur from one locality to another. The lower part of the member contains bioherms at some localities similar to those in the Point Peak Shale Member which underlies the San Saba. In areas where the bioherms are absent, the contact between the Point Peak and the San Saba is the top of the highest significant shale. However, when bioherms are present the boundary is much more difficult to determine. Overlying the San Saba is the Threadgill Member of the Tanyard Formation of the Ellenburger Group and this boundary also is often not distinct. The separation is generally based on the highest glauconite and the approximate faunal boundary. Generally speaking, data on the San Saba in the subsurface are lacking because of the difficulty in distinguishing it from other members of the Wilberns Formation and those of the Tanyard Formation. Due to the difficulty in distinguishing the two rock units and because they are hydrologically connected, the San Saba and the overlying Ellenburger Group are considered a single aquifer (Figure 8).

The San Saba outcrops in southeastern McCulloch County and averages about 280 feet in thickness. In the central portion of Gillespie County, the entire section of Paleozoic rocks has been removed by erosion. However, in the southern part of the county, between Fredericksburg and the Pedernales River, the San Saba is approximately 400 feet thick. In Menard County, the San Saba consists of limestone in the upper part and sandstone in the lower part. The sandstone section has a maximum thickness of about 200 feet and the limestone section is approximately 150 feet thick.

Ordovician

Formations of the *Ellenburger Group* are considered as a single unit in this report because of the lack of data and the difficulty in distinguishing the different formations in the subsurface. Rocks of this group underlie most of the Edwards Plateau. They consist mainly of nonglauconitic limestones and dolomites that range from very fine to coarse grained and are gray to yellowish gray in color. The rocks are generally fossiliferous and chert bearing, especially in the upper part.

Figure 8 shows the outcrop and approximate altitude of the top of the Ellenburger-San Saba aquifer. The Ellenburger outcrops in southwestern Mason County and extends into northeastern Kimble County. Much of the upper part has been eroded causing variations in thickness of the group ranging from approximately 450 to 800 feet in these two counties. Other outcrops of the Ellenburger occur in southeastern McCulloch County and eastern Menard County. The thickness in McCulloch County varies from 280 to 600 feet and averages about 450 feet. The maximum observed thickness in Menard County is about 600 feet in the western part of the county. In Gillespie County, because of faulting and subsequent erosion, the Ellenburger varies from zero to about 1,000 feet in thickness. South of Fredericksburg, the Ellenburger overlies the San Saba Limestone Member and is overlain by the Hensell Sand Member of Cretaceous age.

Permian

Sediments of Permian age are present in the subsurface of the Edwards Plateau. Thickness of these sediments ranges from a few feet along the eastern edge of the Plateau to over 9,000 feet in the Midland basin. In the Eastern shelf area, the Permian is composed of limestone and shales, but in the Midland basin, shales and sandstones predominate. In the southern part of the Eastern shelf, along the common boundaries of Schleicher, Menard, Kimble and Sutton Counties, Permian limestone is in hydraulic contact with the Edwards and associated limestones. This is the only known area on the Edwards Plateau where fresh to slightly saline water occurs in Permian rocks.

Triassic

The *Santa Rosa Formation* is composed mainly of discontinuous lenses of reddish-brown to gray, medium- to coarse-grained, subangular, arkosic sandstone and conglomerate, interbedded with red, green, and blue shale. Also, mica is common throughout the section. A well indurated quartz conglomerate occurs locally near the base either as one thick bed or as alternating thin beds of conglomerate and sand.

In the southeastern corner of Upton County, the Santa Rosa is approximately 100 to 160 feet thick. The formation thickness increases to 560 feet to the northeast in the Midland basin. On the Central basin platform in Upton County, the Santa Rosa is overlain by the Chinle Formation and overlaps the Tecovas Formation. In parts of Crockett, Reagan, Irion, Sterling, and Tom Green Counties the Santa Rosa overlaps

Permian rocks and is truncated by Cretaceous rocks. Surface exposures of the Santa Rosa occur along the North Concho River in Sterling County.

On the Edwards Plateau, the Chinle Formation is present in the subsurface in all or parts of Upton, Crockett, Midland, Ector, Glasscock, Sterling, Irion, and Tom Green Counties. In this area, the Chinle is conformable with the underlying Santa Rosa, and there is an angular unconformity at the top of the Chinle with overlying Cretaceous beds or Quaternary alluvium.

Shales colored from red to maroon and purple are predominant in the Chinle, along with discontinuous lenses of fine-grained, red to gray sandstone and siltstone. Limestone occurs locally as several thick beds and more commonly as cream or red-colored nodules in the shale. Thickness of the Chinle ranges from zero on most of the Edwards Plateau to 570 feet in the Midland basin.

Cretaceous

The last great epicontinental sea advance during post-Jurassic time deposited the Cretaceous sands, shales, and limestones on an eroded land surface. The stratigraphy of the Cretaceous on the Edwards Plateau consists only of the Comanche Series and is relatively simple. The rocks are divided into the Trinity, Fredericksburg, and Washita Groups.

Trinity Group

The units of the Trinity Group, south of the wedge-edge of the Glen Rose Formation, consist of the Hosston, Sligo, Pearsall, and Glen Rose Formations and the Paluxy Sand. The sand unit that overlies the Permian or Triassic rocks north of the wedge-edge of the Glen Rose, is termed the Antlers Formation (Fisher, 1966 p. 8). Figure 9 shows the altitude of the top of the Trinity Group.

The Glen Rose pinch-out (Figure 9) extends eastward from southern Crockett County across Sutton County to the Sutton-Kimble County line, thence northeastward to the northeast corner of Menard County. South of this line the Trinity Group consists of a basal sand unit and an upper limestone unit. Also south of the Glen Rose pinch-out in Uvalde, Kerr, Bandera, Real, Kinney, and Edwards Counties, there occurs a section of strata which Adkins (1932, p. 273) proposed to be included in the Trinity Group and Comanche Series. Imay (1945, p. 1425) correlated this section with the Durango and Nuevo Leon Groups of the Coahuilla Series of Mexico and classified them in ascending order as the Hosston and Sligo Formations. Lozo and Stricklin (1956, p. 74) suggested that these formations are Comanchean in age.

The ***Hosston Formation*** in Uvalde County consists mainly of red sandstone with interbedded shale and limestone. Conglomerate forms the base of the formation which rests upon rocks of Paleozoic age. The thickness varies from 350 to 910 feet.

In Bandera and Kerr Counties, the Hosston is composed of conglomerate and sandstone interbedded with red and green clay and dolomite. Sandy dolomite, dolomitic sandstone, and shale are the principal constituents in the southern parts of the counties. The known thickness of the Hosston in Bandera County ranges from 260 to 335 feet, thinning northward. Erosion of the underlying Paleozoic rocks produced an uneven surface with considerable relief, thus the northward thinning is not uniform.

In Kinney County, west of Brackettville near the Val Verde County line, the drillers' log of an oil test by Mobil Oil Company (J. F. Beidler well) indicates the Hosston to be 200 feet of shale, limestone, red beds, and red sandstone.

The ***Sligo Formation*** in Kinney County is 68 feet thick and consists of sandy shale. In Kerr County and in northern Bandera County, the Sligo is composed of sandy dolomite, dolomitic limestone, and dense, sandy dolomite. In Uvalde County, the formation thickness ranges from 30 to 210 feet and is predominantly limestone interbedded with sandstone and shale.

Both the Hosston and Sligo Formations may be present in Sutton, Real, and Edwards Counties; however, at this writing no known correlation of these formations have been made.

The ***Pearsall Formation*** is composed of three members, in ascending order, the Pine Island Shale, the Cow Creek Limestone, and the Hensell Sand. The Cow Creek and Hensell are known to yield water to wells on the Edwards Plateau.

In Edwards, Real, and Crockett Counties, the Pearsall Formation has not been differentiated other than being separated into three parts or zones. The lower part is composed of alternating beds of varicolored calcareous shale and poorly sorted sand that locally is conglomeritic. The middle part is chiefly limestone and dolomitic limestone with minor amounts of shale and marl. The upper part contains well sorted sand, calcareous shale, and thin-bedded limestone. Thickness of the unit in Edwards County varies from 150 feet in the north to over 400 feet in the south. In Real County, the thickness ranges from 200 feet to over 500 feet, the thicker section being in the southern part of the county.

In Kerr and Bandera Counties, the Cow *Creek Limestone Member of the Pearsall Formation* is predominantly massive, white, gray to brown, sandy, fossiliferous limestone and dolomite. Locally there are interbedcled layers of sand and shale. In Bandera County and northward into Kerr County, the thickness is fairly uniform, 50 to 60 feet. As the Cow Creek continues northward in Kerr County, it thins and grades into shale and sand.

The *Hensell Sand Member of the Pearsall Formation* in Kerr and Bandera Counties is composed of conglomerate, sandstone, shale, marl, and dolomite. The maximum thickness is about 150 feet near the boundary of the two counties. The Hensell thins to the north and south. To the north, the dolomite and marl pinch-out and the Hensell becomes more conglomeritic; whereas to the south, sandstone, shale, and dolomite become more predominant.

In Gillespie County, the Hensell consists of poorly-scrted sand, silt, and clay with beds of limestone common. The upper part of the member is generally fine grained, red to gray in color, and becomes less sandy as it graces upward into the overlying Glen Rose Formation. Conglomerate and coarse, angular sand are in the lower part. Its thickness in Gillespie County ranges from zero in the northern part of the county to over 300 feet in the western part.

In Kimble County, the Hensell is composed of sand, sandstone, siltstone, and clay. It is overlain by the Glen Rose and rests unconformably upon irregularly eroded rocks of Paleozoic age. The thickness of the Hensell varies from zero in the northwest part of the county to 180 feet in the southern part. The pinch-out of the Hensell in Kimble County is approximately on a line extending from the southwest corner to the northeast corner of the county.

On the Edwards Plateau, the *Glen Rose Formation* is a wedge-shaped mass of rocks that thins northward until it is nonexistent along the line previously discussed. The rocks for the most part consist of clays, marls, and limestones, typical of deposition on a continental shelf. Erosion of the limestone and soft marl along stream valleys forms a stair-step or terraced topography.

In southern Crockett County, the Glen Rose consists of thin-bedded limestone and calcareous shale. It overlies the basal sand unit and is overlain by a sand unit called the Paluxy Sand by Iglehart (1967, p. 18). The thickness of the Glen Rose in Crockett County varies from zero to about 100 feet.

The Glen Rose in Sutton County consists of limestone, sandstone, and green and red shale. It is underlain by Permian formations and overlain by the Fredericksburg Group. The thickness ranges from zero to about 420 feet in the southern part of the county.

In Kimble County, the Glen Rose is composed of limestone beds alternating with marl along with some gypsum and anhydrite. The thickness varies from zero in the northwest to 425 feet in the southeast part of the county. The Glen Rose overlaps the Hensell Sand Member of the Pearsall Formation in the southeastern parts of Kimble and Menard Counties, and Paleozoic rocks northwest of the Hensell pinch-out. The Edwards and associated limestones overlap the Glen Rose in Kimble and Menard Counties. In Menard County, the Glen Rose is mainly multicolored clay, silt, and sand, with minor amounts of marl and limestone. The thickness ranges from zero to over 200 feet.

In Kerr County, the Glen Rose can be separated into an upper member and lower member. The lower member is chiefly medium- to thick-bedded, fossiliferous limestone with interbedded sand and shale. The thickness is fairly constant throughout most of the county and ranges from 180 to 210 feet. The contact between the Glen Rose Formation and the underlying Hensell Sand Member is usually placed at the base of the lowest massive limestone beds of the Glen Rose.

The upper member varies in thickness from 330 feet in the northwestern part of Kerr County to 385 feet in the southern part. Shale and nodular marl predominate in the upper member, alternating with thin-bedded impure limestone. There are two marker horizons of porous anhydrite in the upper member, one of these evaporite beds is located near the middle of the upper member. The base of the lower anhydrite bed is usually selected as the boundary between the two members.

In Bandera County, the Glen Rose is predominantly a rudistid limestone, with minor amounts of sand, clay, dolomite, and anhydrite. The limestone is thin bedded in the upper member and massive in the lower member. Since the contact between the Hensell and the Glen Rose is gradational, the separation is arbitrarily placed at the base of the lowest massive limestone bed in the lower member of the Glen Rose. The contact with the overlying Comanche Peak Formation is also gradational. The lower member of the Glen Rose in Bandera County thickens from 190 feet in the north to 380 feet in the south.

The upper member of the Glen Rose is mainly blue to yellowish-brown shale, marl, and thin-bedded fossiliferous limestone with two evaporite sections. The upper evaporite beds, which occur in the middle of the member, consist of anhydritic marl and dolomite. Both evaporite sections are characterized on electric logs by high resistivity kicks, and on the outcrop they occur as brown, ferruginous, dolomitic clay with the anhydrite having been removed by leaching. In the northern part of Bandera County, the upper member is about 385 feet thick increasing to about 440 feet in the southern part of the county.

The lithology of the Glen Rose in Kinney County is similar to that in Bandera County. The thickness of the Glen Rose in Kinney County varies from 1,100 feet in the north-western part of the county to about 1,700 feet in the south-central part.

Thickness of the Glen Rose in Edwards and Real Counties ranges from 450 to 750 feet and from 480 to 780 feet respectively; the thicker sections occur in the southern parts of these counties.

In southern Crockett County, Iglehart (1967, p. 18) refers to a sand section between the Glen Rose and Comanche Peak Formations as the *Paluxy Sand.* The sand is not present above the Glen Rose at all locations in southern Crockett County and the thickness varies considerably, reaching a maximum of 75 feet in the southern part of the county.

For the purpose of this report, the basal sand unit that overlies the Permian or Triassic rocks north of the wedge-edge of the Glen Rose Formation is termed the *Antlers Formation.*

In Ector, Midland, Glasscock, Sterling, Upton, Reagan, Irion, Crockett, Coke, Tom Green, Schleicher, and Sutton Counties, the Antlers consists of buff to gray, fine- to medium-grained, cross-bedded, quartz sand and sandstone interbedded with lesser amounts of red, gray, and purple shale. In some places, a fine gravel occurs at the base, these areas should correlate with the topographic lows of the eroded pre-Cretaceous surface. The induration of the sand varies from place to place, from tightly cemented to friable or poorly cemented. The latter is commonly referred to by local drillers as *pack sand.* The base of the Antlers is often difficult to determine due to the reworking of Triassic and Permian age red shales by Cretaceous seas.

Thickness of the Antlers varies locally because the sand was deposited on an eroded surface of low to moderate relief (10 to 100 feet). The maximum thickness is about 254 feet in west-central Reagan County. In addition to Reagan County, thick sections of the Antlers also occur in eastern and northeastern Upton County (216 feet), north-central Crockett County (224 feet), southwestern Glasscock County (250 feet), and southwestern Schleicher County (237 feet). In Ector County, the thickness ranges from about 70 to 120 feet.

The Antlers is absent in an area of the northern and central parts of the Plateau in parts of Concho, Kimble, McCulloch, Menard, Schleicher, Sutton, and Tom Green Counties. This is due to the presence of “highs” of resistant Paleozoic deposits which were never covered by the Cretaceous (Trinity) seas (Cartwright, 1962, p. 694).

Fredericksburg Group

The *Walnut Formation* is either thin or absent over most of the Edwards Plateau region. On Mount Margaret, near Tennyson in Coke County, the Walnut consists of 22 feet of brown sand and sandy marl overlying the Antlers and underlying the Comanche Peak Formation. In Tom Green County, the Walnut consists of 5 to 15 feet of yellowish, sandy marl and clay. The Walnut in Gillespie County is a yellow clay only a few feet thick that grades upward into the overlying Comanche Peak. Previous investigators may have included some of the Walnut Formation with the Comanche Peak.

The *Comanche Peak Formation* is present either at the surface or in the subsurface over the entire area of the Edwards Plateau. It is typically a chalky to argillaceous, nodular limestone and overlies the Walnut Formation, where it is present, and underlies the Edwards Formation.

In Tom Green County, the Comanche Peak is about 100 feet thick and consists of soft, yellowish, chalky and sandy limestone in the lower part and massive, more resistant beds of limestone in the upper part.

To illustrate the variation in thickness of the Comanche Peak limestone in the southern part of the Edwards Plateau, the following examples are given:

County	Thickness in feet	County	Thickness in feet
Gillespie	30	Real	70
Uvalde	60-90	Bandera	25-60
Kinney	25	Kerr	20-50
Edwards	45-60		

In Crockett County, the combined thickness of the Comanche Peak and the Edwards is about 190 feet, and consists of soft, yellow to white, nodular, marly limestore in the lower part and massive, chert-bearing limestone in the upper part. In Upton County, this same section is about 168 feet thick and is composed of yellowish-brown, massive nodular limestone and calcareous clay. The Edwards and associated limestones in Ector County probably consists of only the Comanche Peak, which varies in thickness from zero to about 50 feet. It overlies the Antlers, and the best exposures are along Concho Bluff in the western part of the county.

In Coke County on Mount Margaret, the Comanche Peak consists of 35 feet of white, massive to nodular limestone and brown marly to sandy limestone, and is overlain by the Edwards Formation. In parts of Concho and McCulloch Counties, the Edwards has been removed by erosion and the Comanche Peak occurs at the surface.

The ***Edwards Formation*** is a thin-bedded to massive, fossiliferous, honey-combed limestone which forms the relatively flat topographic divides with steep-walled stream canyons on the Edwards Plateau. The limestone generally contains chert or flint nodules with dolomitic limestone in the lower part. In Sutton and nearby counties, the Edwards is a granular to crystalline, dolomitic limestone called ***brown lime*** or ***brown sand*** on local well driller's logs. Caverns or caves and smaller solution channels are common in the Edwards.

In Gillespie and Menard Counties, Barnes (1943, p. 40) studied isolated gypsum deposits in the Edwards which he believed to be parts of a formerly widespread evaporite horizon. To this evaporite horizon, which occurs about 140 feet above the base of Edwards, Barnes applied the name ***Kirschberg.*** The thickness of the Edwards in Gillespie County is about 200 feet.

In Uvalde County, the Edwards ranges from 50 to 100 feet in thickness and consists of massive lithographic to medium-grained limestone with a few beds of dolomite. The limestone contains minor amounts of chert.

In Kinney County, the Edwards is about 575 feet thick overlying the Comanche Peak and underlying the Georgetown. The lithology of the Edwards in Kinney County is mainly massive-bedded, light to dark gray limestone with some marl which is thin and flaggy near the base.

The Edwards in Tom Green County is massive, gray limestone with some porous, chalky limestone beds. Honey-combed limestone and chert or flint nodules are common. The thickness varies from 50 to 200 feet.

In Bandera, Edwards, Real, and Kerr Counties, the Edwards and the Georgetown Formations are considered as one unit and have not been differentiated. In these counties the thickness of the unit is about 500 feet. In Menard County, the Comanche Peak, Edwards, and Georgetown are considered as a single unit that ranges in thickness from zero to 250 feet; and in Kimble County this unit varies in thickness from 380 to 480 feet.

The ***Kiamichi Formation*** is recognized only in the southern part of the Edwards Plateau. Lithology of the formation in Uvalde County is described as thin to flaggy, dark gray to buff, petroliferous limestone. Zones of solution breccia occur in the limestone, along with bedded and nodular flint. A few beds of black, petroliferous shale occur in the upper part of the formation. Leached zones are present at or near the outcrop due to the removal of gypsum by weathering. Downdip, the gypsum and the limestone increase in thickness as the depth increases. In Uvalde County, the thickness of the Kiamichi Formation ranges from 155 to 210 feet (Welder and Reeves, 1962, p. 17).

In Kinney County, the Kiamichi is composed mainly of black shale, black and brown limestone (possibly petroliferous) and anhydrite. This section of strata is about 200 feet thick (Bennett and Sayre, 1962, p. 30).

According to White (1968, p. 19), H. D. Eargle assigned 93 feet of calcareous clay and marl on King Mountain in Upton County to the Kiamichi Formation.

Washita Group

Adkins (1932, p. 361), in discussing the Washita Group, stated that a large area in the western part of the Edwards Plateau, comprising Crockett, southern Upton, Reagan, Irion, Schleicher, western Menard, Sutton, and northern Edwards Counties is capped by the Washita. In the northern part of the Plateau, the ***Georgetown Formation*** is the most extensively exposed unit of the Washita Group due to removal of part or all of the Del Rio and Buda Formations by post-Cretaceous erosion.

In Crockett County, the Georgetown consists of soft, nodular limestone and marl in the lower part and massive, more resistant, fossiliferous limestone in the upper part. The thickness varies from 340 to 400 feet. An unconformity separates the Georgetown from the underlying Edwards. The Buda occurs at higher elevations in Crockett County.

In Upton County, the Washita Group has not been differentiated and consists of about 195 feet (possibly up to 250 feet) of calcareous clay, marl, and thin to massive-bedded limestone. The limestone caps the slopes of clay and marl.

In Uvalde County, the Georgetown ranges from about 310 to 400 feet in thickness. It overlies the Kiamichi and is overlain by the Del Rio Formation. The limestone is white and fine grained with flint beds or nodules occurring in the section between 140 and 275 feet above the base of the Georgetown. Near the top of the Georgetown, the limestone becomes more argillaceous as it grades upward into the overlying Del Rio.

The Georgetown and the Edwards Formations in Kinney County are so similar that, according to Bennett and Sayre (1962, p. 31-32), faunal studies of the fossils are essential in differentiating the two formations. In the eastern part of the county, Bennett and Sayre (1962, p. 31) recorded a 55-foot section of Georgetown which consisted of very fine-textured, massive, nodular, light-gray limestone intercalated with thin beds of marl. lmlay (1945, p. 20) recorded 505 to 550 feet of Georgetown in the Mobil Oil Company Wardlaw well 10-3/4 miles east of the city of Del Rio in Kinney County.

The *Buda Formation* in Crockett County consists of thin-bedded, hard, sparry limestone at the top and microcrystalline limestone at the bottom, separated by yellow, fossiliferous, nodular marl. A maximum of about 40 feet of Buda caps the high flat divides n Crockett County.

In Uvalde County, the Buda is a dense, very fine-grained, massive limestone whose color ranges from white to gray to pink. On the outcrops, mainly in the southern part of the county, the Buda weathers to a light gray or brown, and along the streams it may have a white, nodular appearance. The Buda ranges from about 70 feet near Sabinal to about 100 feet in the western part of Uvalde County. It lies conformably on the Del Rio Formation and is overlain unconformably by the Eagle Ford Formation.

In Kerr County, the Buda has a maximum observed thickness of 15 feet and in Kinney County the thickness ranges from 65 feet on the outcrop at Turkey Mountain to 119 feet in the subsurface in the southwest part of the county. The maximum thickness of the Buda in Edwards County is 20 feet, and in Real County the maximum thickness is about 10 feet.

Tertiary

The Tertiary System is represented by the *Ogallala Formation* along the northern edge of the Edwards Plateau. The Ogallala consists of alternating beds of clay, caliche, gravel, and sand. The gravel and sand, for the most part, is poorly sorted and unconsolidated. In parts of Ector, Midland, Martin, Howard, and Glasscock Counties, the Ogallala lies unconformably on Triassic and Cretaceous rocks and is overlain by Quaternary alluvium over much of this area. At Panther Creek, in northern Glasscock County, the Ogallala appears to have a thickness of some 250 feet (Figure 10).

Quaternary

Alluvial deposits of Pleistocene and Recent age occur along nearly all of the stream courses on the Edwards Plateau (Figure 6). These deposits consist of sand, gravel, silt, and clay derived from the erosion of the underlying rocks, and occur primarily as terrace and flood-plain alluvium. The terrace material along the North and Middle Concho Rivers and their tributaries north and west of San Angelo ranges in thickness from a few feet to as much as 120 feet in Sterling County. In Uvalde County, north of the Balcones fault zone, the alluvial deposits attain a maximum thickness of about 100 feet. The maximum observed thickness of alluvium in Kerr, Edwards, Real, and Kimble Counties varies between 40 and 50 feet. In Sutton and Gillespie Counties, the alluvium appears to be about 25 feet or less in thickness, but locally in Sutton County may reach a thickness of about 100 feet. Along Live Oak Creek and Howard's Creek in Crockett County, the thickness ranges from a few inches to over 200 feet.

Geology as Related to the Occurrence of Ground Water

The aquifers that contain fresh water on the Edwards Plateau are listed in order of their importance and development.

Edwards-Trinity (Plateau) Aquifer

The term *Edwards-Trinity (Plateau) aquifer* as used in this report includes all the rocks from the base of the Antlers Formation (Trinity Group) to the top of the

Georgetown Formation (Washita Group). In parts of Sterling, Irion, Reagan, and Crockett Counties, where the Santa Rosa Formation subcrops beneath the Antlers, the two formations are considered to be a single hydrologic unit (Figures 10, 11, and 12). South of the Glen Rose Formation pinch-out, the Edwards-Trinity (Plateau) aquifer includes all rocks from the top of the Glen Rose to the top of the Georgetown Formation. The approximate altitude of the base of the Edwards-Trinity (Plateau) aquifer is shown on Figure 13.

Water in the Edwards-Trinity (Plateau) aquifer flows generally in a southeasterly direction. However, locally the direction of flow will vary; for example, near the major streams the flow of ground water will be towards these streams. To a certain extent, the ground water flow conforms to the surface topography.

From a regional standpoint, the Edwards and associated limestones and the Antlers Formation constitute a single aquifer. However, in some areas the zone of saturation is below the limestone and the fresh ground water (less than 1,000 milligrams per liter dissolved solids) is confined to the Antlers. The areas where the fresh water occurs only in the Antlers are Ector and Midland Counties and in parts of Upton, Glasscock, and Reagan Counties. In parts of Crockett, Reagan, Irion, Sterling, and Tom Green Counties, the Santa Rosa Formation is included with the Antlers and Edwards and associated limestones to compose the Edwards-Trinity (Plateau) aquifer. In these counties, pre-Cretaceous erosion removed the Chinle Formation that had overlain the Santa Rosa Formation; thus, the Antlers was deposited directly on the Santa Rosa.

Only a small amount of water is found in the Georgetown Formation in the northern part of the Edwards Plateau due to its limited distribution and occurrence above the zone of saturation. In the southern part of the Plateau, the Georgetown contributes a major portion of ground water to wells developed in the Edwards and associated limestones.

The Edwards Formation contains water in varying amounts in solution cavities, fractures, and dolomitic limestones over the Plateau except for areas where the water is confined to the Antlers Formation and to Permian rocks.

Along the east and southeastern edge of the Plateau, the saturation of the Edwards-Trinity (Plateau) aquifer is thin and ground-water discharge through seeps and springs is rapid. This is due in part to the high topographic position of the formation and stream erosion. The areas where the saturated thickness appears to be the greatest are in southern Val Verde County and in Reagan County, three or four miles southwest of the town of Big Lake. The apparent saturated thickness near Big Lake exceeds 700 feet and includes rocks of the Edwards and associated limestones, the Antlers, and the Santa Rosa. Reported discharge of wells developed in the Edwards-Trinity (Plateau) aquifer vary from less than 50 to over 1,000 gallons per minute (gpm).

Alluvium Aquifer

Alluvium occurs along the North and Middle Concho Rivers and their tributaries. These deposits range in thickness from a few feet to as much as 250 feet, and are generally in hydraulic contact with, and probably receive recharge from the Antlers.

The alluvial deposits along the Frio, Nueces, Sabinal, and Guadalupe Rivers in the southern part of the Plateau are recharged by stream flood waters and discharge from the Edwards and associated limestones. Maximum thickness of the alluvium in these areas ranges from 25 feet to about 100 feet. Maximum thickness of alluvium in western Crockett County along Live Oak Creek and Howard's Creek is about 200 feet.

The saturated thickness of the alluvium varies from less than 30 feet to about 200 feet. The greatest saturated thickness is along the North Concho River in northeast Glasscock and northwest Sterling Counties. Reported discharge of wells developed for irrigation range from less than 100 to 1,500 gpm.

Lower Cretaceous Aquifer

The formations which, for this report, are referred to as the lower Cretaceous aquifer are in ascending order, the Hosston, Sligo, Pearsall, and Glen Rose. In the areas where all are present, they generally are in hydrologic connection and are considered as one aquifer. Locally, any one of these formations may constitute an aquifer.

Since these formations occur only south of the Glen Rose pinch-out, they are usually developed near the eastern and southern edges of the Edwards Plateau. Also, some wells produce from these formations along the streams where the Edwards and associated limestones have been removed by erosion.

The Hosston and Sligo Formations range in thickness from a few feet along the northern limit to about 1,200 feet in the southern part of Kinney, Uvalde, and Val Verde Counties. Fresh to slightly saline water is yielded to wells in Bandera and Kerr Counties. In

Kinney, Uvalde, and Val Verde Counties, the Hosston and Sligo either yield saline water, or have not been developed in wells and the water quality is not known. Maximum reported yield of this aquifer is greater than 1,000 gpm.

The Cow Creek Limestone and Hensell Sand Members of the Pearsall Formation are present in the subsurface of the southern part of the Edwards Plateau. Thickness of these members range from a few feet near the northern limit to about 250 feet in Kerr, Bandera, and Uvalde Counties. Fresh to slightly saline water is yielded to wells developed in the Cow Creek and Hensell in Kimble, Kerr, and Bandera Counties. The Hensell may contain fresh to slightly saline water in the southern parts of Edwards and Real Counties, however, no wells of record penetrate the Hensell. Discharge of wells developed in the Cow Creek and Hensell is reported to range from a few gallons per minute to about 300 gpm.

The Glen Rose Formation is wedge-shaped and composed of limestone, marl, shale, and evaporites which range in thickness from a few feet near the northern limit to about 1,700 feet in the southwestern part of the Plateau. Wells have been developed in the Glen Rose in areas where the overlying sediments have been removed by erosion or do not contain the desired amount of ground water. Most of the wells are located in southern Real, northern Uvalde, eastern Kerr, and Bandera Counties. In the southeastern part of the Plateau, the Glen Rose has been divided into the upper member and lower member. The upper member yields small amounts of slightly saline water from the limestone and small to moderate amounts of water from evaporite beds. The water from the evaporite beds is high in sulfate content and unfit for most purposes. The lower member yields small to moderate amounts of fresh water from massive limestones.

Hickory Aquifer

The Hickory Sandstone Member of the Riley Formation ranges in thickness from a few feet on the outcrop to 500 feet in southeastern McCulloch County.

We ls developed in the Hickory are mainly confined to the outcrop area east of the Edwards Plateau in McCulloch, Mason, and San Saba Counties. Several municipal wells are completed in the Hickory, such as the wells at Brady and Melvin in McCulloch County, The city of Eden in Concho County has one well completed in the Hickory which is used as a supplementary water source. The city of San Angelo has completed two test wells in the Hickory in southeastern Concho County and western McCulloch County.

Near the outcrop the Hickory is under water-table conditions, and downdip the aquifer is under artesian pressure. The movement of water within the Hickory is both downdip and laterally. Reported discharge of wells range from less than 100 to about 1,000 gpm.

Ellenburger-San Saba Aquifer

The Ellenburger-San Saba aquifer is composed of the San Saba Limestone Member of the Wilberns Formation of Cambrian age and the Ellenburger Group of Ordovician age. Because of the difficulty in separating these units in the subsurface and the fact that they are hydrologically connected, they are considered as a single aquifer.

Well development in the Ellenburger-San Saba is principally near the outcrop east and southeast of the Edwards Plateau in McCulloch, San Saba, and Gillespie Counties. A few wells have been developed in this aquifer on the Plateau in southwestern McCulloch, eastern Menard, and northeastern Kimble Counties. Reported discharge of wells developed in the Ellenburger-San Saba aquifer exceed 1,000 gpm; however, most wells discharge less than 500 gpm.

Ogallala Aquifer

The Ogallala Formation of Tertiary age is the principal water-bearing unit on the High Plains. Along its southern limit, which is adjacent to the Edwards Plateau in Ector, Midland, and Glasscock Counties, the Ogallala is an important source of ground water locally.

Water in the Ogallala flows to the south and southeast, except in local areas of heavy pumping of the aquifer where the direction of flow is toward the area of withdrawal.

The saturated thickness of the Ogallala varies greatly. In Midland County, the saturation ranges from about 10 to 62 feet with an average of about 30 feet. The average saturation of the Ogallala in Ector County is 55 feet, ranging from a low of 5 feet to a high of 81 feet. The greatest saturated thickness is in northwestern Glasscock County where the average is 76 feet and ranges from 32 to 112 feet. Reported discharge of wells developed in the Ogallala in Ector, Glasscock, and Midland Counties ranges from about 10 to 1,500 gpm. Wells developed along the northern edge of the Plateau likely penetrate both the Ogallala and Antlers Formations.

Permian Aquifer

Several stratigraphic units of the Permian System are in apparent hydraulic contact with the overlying Cretaceous units and may contain small amounts of fresh to slightly saline water in parts of Irion, Sterling, Tom Green, Crockett, and Coke Counties. The units which appear most promising as a source of ground water, solely on the basis of lithology, are the Yates, Seven Rivers, and Queen Formations. Two other possible sources of ground water from the Permian are the Bullwagon Dolomite Member of the Vale Formation and the San Angelo Formation which also occur beneath the Cretaceous in southeastern Tom Green and northwestern Schleicher Counties.

Permian limestone contains fresh to slightly saline water in the area of the common corners of Kimble, Menard, Schleicher, and Sutton Counties. The Permain is overlain by the Edwards and associated limestones in this area and is recharged by water from the Cretaceous.

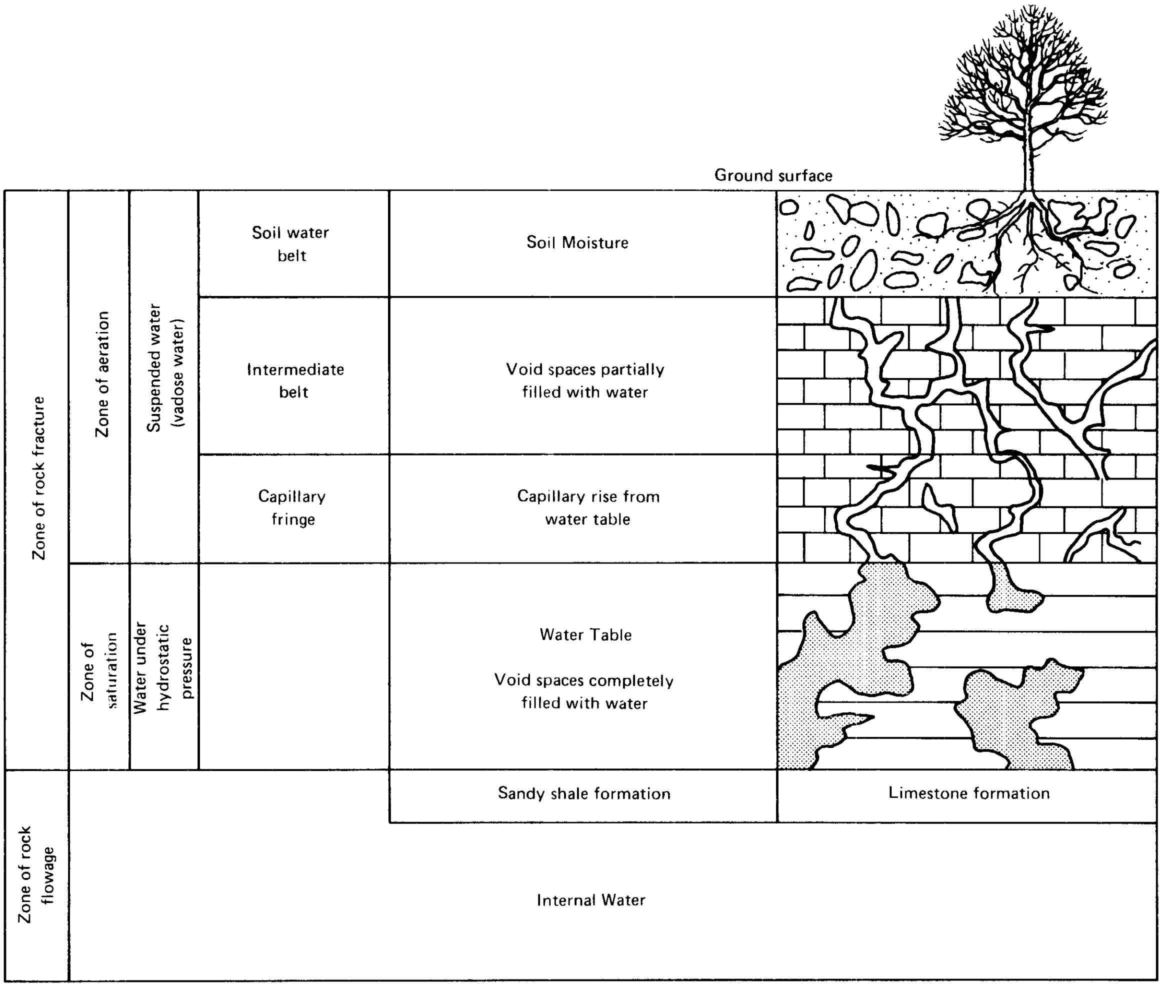
GROUND-WATER HYDROLOGY

The course that water travels through the atmosphere, on the land surface, under the ground, in lakes and the ocean, and then again to the atmosphere by evaporation is called the hydrologic cycle (Figure 14).

The Earth's Ground-Water Reservoir

To show the earth's reservoir characteristics with respect to percolating waters and the storage of water requires that the earth's crust be divided into its various components as shown in the following illustration.

The lithosphere or earth's crust is separated into a zone of rock flowage and a zone of rock fracture. Within the zone of rock flowage that is relatively deep within the earth, interstices or void spaces may be absent because the rocks are in a state of plastic flow due to the stresses exceeding the elastic limit. Internal water will not be dealt with in this study.



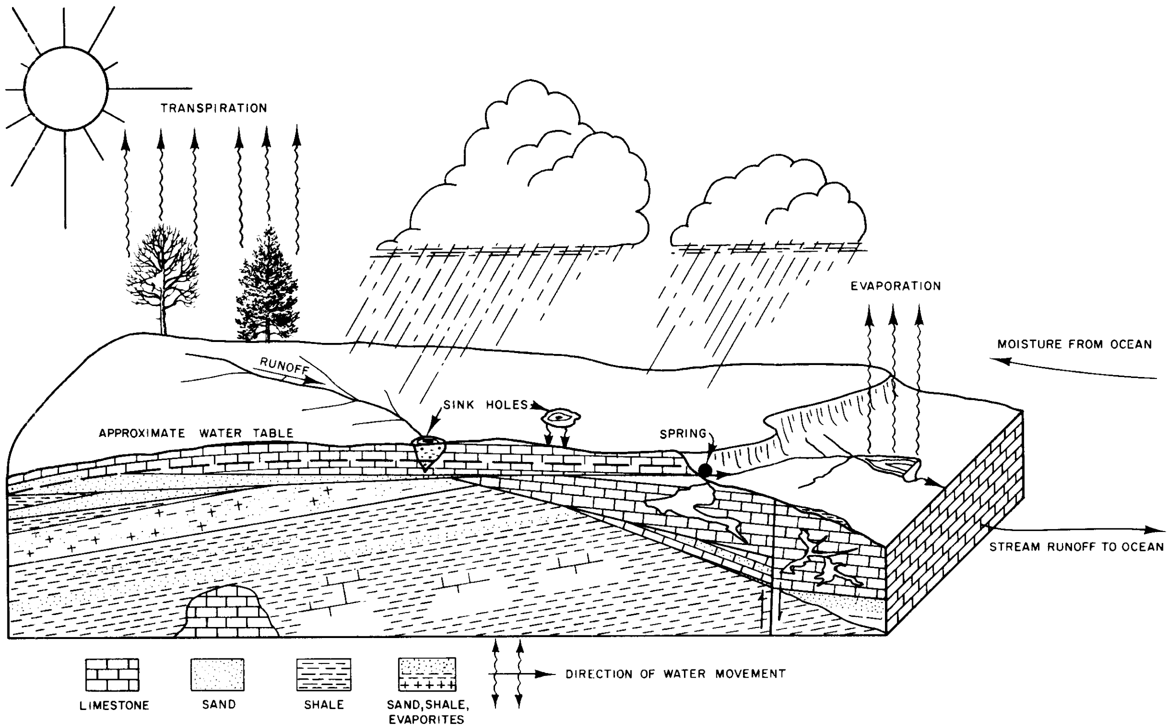


Figure 14.—Hydrologic Cycle

Pertinent to this report and ground-water hydrology, however, is the zone of rock fracture and its subdivisions—the zone of aeration and the zone of saturation.

In the zone of aeration, water is suspended by molecular attraction or capillary forces and may be influenced by gravitational forces as it moves downward to the saturated zone below. This zone is further divided into three belts—the belt of soil moisture, the intermediate belt, and the capillary fringe.

The belt of soil moisture is the layer of the earth's crust that furnishes water to vegetation. Thickness of this belt may be from a few inches to tens of feet. Under certain conditions water may pass downward beyond the reach of roots of ordinary vegetation.

Phreatophytes are plants that do not depend entirely upon the soil belt for moisture; hence, occasionally their roots may extend downward and tap the capillary fringe at shallow depths along streams.

The intermediate belt lies below the soil moisture belt and acts as a conduit for percolating water influenced by gravitational forces. Some of the water in this belt may progress downward to the capillary fringe while some remains suspended by molecular and capillary attraction and is not recoverable by wells.

The capillary fringe lies between the intermediate belt and zone of saturation below, and contains water held above the water table by capillary forces greater than downward gravitational forces. Silts and clays may have a thick fringe while coarse sands and gravels may have one that is insignificant. In limestones, the capillary fringe may be nonexistent.

With regard to this study, the focus of attention will be on the zone of saturation; that is, the interval of the earth's crust in which water completely fills the pore spaces of the rocks and is potentially recoverable by wells for use by man. The occurrence of ground water in the saturated zone will be covered later in this report.

Source of Ground Water

Recharge to the ground waters of the Edwards Plateau is derived entirely from precipitation, whether it be from the region's characteristic spring and fall rains or rare winter snows. Before percolation to the aquifers begins, there are many factors that affect the course that the water will take on its way to the water table.

Some of these factors are surface runoff, soil moisture content, evaporation, transpiration by vegetation, wind velocity, temperature, and permeability of both the soils and underlying rocks to the water table surface.

Surface ruroff is that portion of the precipitation that reaches the stream channels without first percolating to the aquifer. Consequently, these waters never become ground water.

The soil moisture content is the water held in the soil by molecular attraction. Soil moisture varies depending upon the vegetative cover, elapsed time from last rainfall, wird velocity, infiltration capacity, and capillary potential. Infiltration capacity is the maximum rate that a soil may absorb water. Capillary potential is the measure of the force required to remove moisture from the soil. Percolation to the aquifer begins when downward forces exceed the capillary potential. If the soil is thin or nonexistent, water may run directly into limestone through cracks, joints, and solution openings.

Evaporation, or the change of water into vapor that passes into the atmosphere, is influenced by temperature, humidity, and wind velocity. In the Edwards Plateau region, the annual rate of evaporation is three times greater than the annual rate of precipitation, thus creating a perpetual low soil moisture content that retards percolation except under the most ideal conditions. Percolation usually occurs during relative short periods after rainfall.

Transpiration is the emission of water vapor to the atmosphere by plants. The rate of transpiration varies throughout the life of the plant depending upon the temperature, sunlight, moisture available, degree of plant development, and other atmospheric conditions. Because some factors have the same influence on both evaporation and transpiration in much the same way, namely temperature and wind velocity, they are usually treated together as evapotranspiration. Under any given set of conditions, the evapotranspiration requirements must be met before the soil moisture capacity is reached and percolation begins. High temperatures and high wind velocities increase evapotranspiration and are major factors in determining the recharge potential to water-bearing formations.

Soil permeability is an expression of the ability of water to pass through pore spaces of the soil and varies throughout the Edwards Plateau from less than 0.06 to 0.63 inches per hour. Rain intensities greater than these rates will produce surface runoff. Soils developed over unconsolidated alluvium or colluvium tend to facilitate the downward movement of water to the aquifer.

Exposed bedrock or extremely thin soils are common over much of the Edwards Plateau. In these areas, soils do not play an important role with respect to the recharge; hence, water descends unhindered through the zone of aeration to the aquifer.

Limestone is the predominant rock underlying the Edwards Plateau soils. The permeability of the limestone is not necessarily due to intergranular pore space as in sandstones, but more to joints, crevices, and solution openings that have been enlarged by solvent action of water charged with carbon dioxide. In areas where this water action is extensive and the limestone is somewhat in a pure and brittle state, these openings become quite large, producing solution channels and caverns where large quantities of water may be stored. Where this dissolving action has become highly developed, a karst topography is characteristic, and numerous sink holes can be seen on the surface of the land. These depressions are caused by the slumping or caving of the ceilings of caverns. Consequently, the permeability may be high but irregularly distributed, and recharge to the water table is direct with little interference from the soils and other surface conditions. Runoff may extend for short distances before it disappears into the subsurface. Rapid recharge of this type may cause water-table mounds that dissipate after rainfall periods.

The source of water to the alluvium aquifer in the Edwards Plateau region of Texas is from precipitation upon the surface of the outcrop and from water-bearing formations in hydraulic contact with the alluvium. The latter case is evidenced by springs that maintain the baseflow of the South Concho, San Saba, North Llano, South Llano, Pedernales, Nueces, and Frio Rivers. The alluvial deposits in these streambeds contain relatively unconsolidated sediments; therefore, recharge rates should be high. A deterrent to efficient percolation would be heavy canopies of brush, such as mesquite and salt cedar, along many of the stream courses. These phreatophytes use large quantities of water when it is available.

Determination of the amount of recharge to the ephemeral stream sediments of the Plateau and adjoining areas is difficult to ascertain because these data are not available.

The Hickory Sandstone Member crops out principally in McCulloch and Mason Counties. Precipitation upon this sandy surface provides the main source of recharge to the aquifer. Other possible sources of water may come from streams traversing the outcrop and from underlying Precambrian granites and gneisses that have been fractured by faulting, and whose outcrop lies at higher elevations than the Hickory.

Interformational leakage through the overlying Cap Mountain Limestone and Lion Mountain Sandstone Members may also contribute water to the Hickory.

The source of recharge to the Ellenburger-San Saba aquifer is precipitation upon its outcrop in San Saba, southeast McCulloch, eastern Menard, southwestern Mason, southwestern Kimble, and Gillespie Counties (Figure 8). Overlying formations such as alluvium and the Hensell Sand Member may provide some recharge. Also, recharge may occur in faulted areas where permeable beds are adjacent to the aquifer or hydrostatic pressure differential permits water movement along fault planes.

Recharge to the Glen Rose Formation and the Hensell Sand Member occurs on the outcrop and from percolation through the overlying Edwards and associated limestones. Some water may be contributed by the Cambrian and Ordovician aquifers where they are in contact with the Lower Cretaceous rocks.

Occurrence of Ground Water

On the Edwards Plateau, ground water occurs in the saturated zones of the rock strata. In the Antlers Formation, water occupies the interstices or pore spaces between the sand grains. The percent porosity and the permeability, or ability of the water to move through the formations, are dependent upon the grain size, shape, sorting, packing, and degree of cementation. More important, however, than the foregoing characteristics of the sediments, is the cementing material. Extensive calcite cementing in parts of the Antlers may retard ground-water movement and reduce storage capacity.

With regard to the Edwards and associated limestones, the amount of water occupying the void spaces depends upon the type of porosity, whether primary or secondary. Primary porosity originates at the time of deposition of shell fragments, precipitated limey muds, calcite sand, talus deposits, reef masses, and accumulations of the remains of small planktonic organisms. Much of this porosity is lost soon after deposition due to compaction and induration and probably plays a minor role with respect to water storage in the Edwards Plateau.

More important, from the standpoint of ground-water storage and production, is the secondary porosity in dolomites and limestones. The diagenetic, post-depositional change of calcite to dolomite results in a corresponding 13 percent volume reduction of the lithified rocks, thus creating this amount of additional void space. In Sutton County, drillers inadvertently refer to these dolomite water-bearing layers as "sugar sands". Probably the most important form of secondary porosity on the Edwards Plateau is caused by the solution of limestone along fractures, joints, and around fossils. These are the zones most important with regard to water production, along with underlying saturated sands of the Antlers Formation. Water may occur in relatively small openings to those the size of caverns. Solution channels and honeycomb limestone are common forms of secondary porosity developed by the solvent action of ground water.

The ground water in the saturated zone may occur under water table, or unconfined, and artesian, or confined conditions. When the upper surface of the saturated zone has direct contact through the aerated zone to the land surface and is therefore under atmospheric pressure, as a lake surface would be, the aquifer is under water-table conditions. If the saturated zone is overlain by a relatively impervious bed, or aquitard, that restricts the upward movement of water causing the aquifer to be under pressure, then artesian conditions prevail. When an artesian well is drilled, water will rise above the level at which it was encountered. A water-level recorder well in southwestern Glasscock County shows daily barometric pressure changes which are indicative of artesian conditions.

Where the Antlers Formation crops out, water-table conditions persist except where clay lenses may act as aquitards of confinement to underlying saturated sandstones. These lenses are present in areas where the Triassic rocks have been reworked during deposition of the Antlers. Water-table conditions also exist where joint systems are developed. The joint systems increase the susceptibility of rocks to the disolving action of water resulting in larger passageways through which the water may move. Areas of this type are noticable by the karst topography such as may be observed in Schleicher County. Water-table conditions also probably prevail in the vicinity of discharge basins along the South Concho, San Saba, and Llano Rivers.

Throughout the Edwards Plateau, drillers quite often report that water will rise in a well above the level at which it was encountered; consequently, water-table conditions may not be as prevalent as previously reported. In Upton County, White (1968, p. 20) reports the Antlers is confined in the southeastern corner of the county where the saturated sands are overlain by beds of low permeability at the base of the Edwards and associated limestones. In this area, he reports that water will rise as much as 25 feet in wells, and in some wells hydrogen sulfide gas is released after being entrapped by the confining strata.

In alluvial deposits, water occurs in the void spaces of sediments made up of clays, sands, gravels, boulders, and conglomerates. The surface of the saturated zone makes up the water table in areas where these deposits occur.

The occurrence of ground water in the interstices of the Hickory Sandstone Member is under both water table and artesian conditions. Mason (1961, p. 21) states that clay lenses in the outcrop area of the Hickory impede the vertical movement of water. Where these lenses exist, the wells have artesian pressure and may even flow; otherwise, unconfined water occurs. North and west of the outcrop area, the Hickory is confined by overlying formations.

Mount and others (1967, p. 72) describe the occurrence of water in the Ellenburger-San Saba aquifer as being in vugular and cavernous openings as well as in fractures and joints enlarged by solution. He also reports that the aquifer is under artesian pressure with few exceptions.

In the southeastern portion of the study area, through Kimble, Gillespie, and Kendall Counties, ground water occurs in the Lower Cretaceous aquifers. These aquifers in descending order are the Glen Rose Formation, Hensell Sand and Cow Creek Limestone Members of the Pearsall Formation, and the Sligo and Hosston Formations.

In Kendall County, most of the water in the Glen Rose limestones occurs under artesian pressure because of the presence of relatively impervious beds which act as confining layers. The upper member of the Glen Rose has solution channels which contain the water. These channels are tubular and have developed parallel to the bedding planes of the thin-bedded limestone. In the thick-bedded limestone of the lower member, vertical connection of solution channels is greater, which allows for more water to be stored in the rocks.

The Cow Creek Member is predominantly massive, white, fossiliferous limestone. Ground water probably occurs in the vugs developed in the fossiliferous portion of the limestone.

The Hensell Member is comprised of loosely cemented conglomerate, sand, sandstone, shale, and marl. Where the Hensell is an important aquifer, ground water is contained primarily in the sands and sandstones.

The Sligo Formation consists mainly of sandy dolomite and dolomitic limestone which are known to contain ground water in Kendall County. The Hosston Formation contains conglomerate, sandstone, and dolomite interbedded with shale. Ground water occurs in this formation in quantities sufficient to maintain irrigation wells in Kendall County.

Direction and Rate of Ground-Water Movement

Ground water moves in the direction of the hydraulic gradient from areas of recharge to areas of discharge. The movement is perpendicular to lines of equal elevations on the water-table, or piezometric, surface.

In the Edwards-Trinity Plateau aquifer, geological structure has the greatest influence on the direction of ground-water movement. Regionally, the base of the Cretaceous slopes to the south and southeast, and this is reflected by the surface of the saturated zone of the Edwards-Trinity (Plateau) aquifer (Figure 15). Local changes to this trend occur in areas of artificial discharge such as in the St. Lawrence irrigation area of south central Glasscock and north central Reagan Counties. Here, a regional cone of depression of the water table has been created and water moves toward the center of development or pumpage. Figure 15 also indicates water movement towards the major stream drainage courses. At the head of most of these major streams, water flows from springs. In the southwestern part of the Plateau area, ground water moves to the Rio Grande; in the north, northeast, and central parts, movement is to the Colorado River and its tributaries; and in the southeastern part, movement is to the Nueces, San Antonio, and Guadalupe Rivers.

In the Edwards and associated limestones, lines perpendicular to the water-level contours show the direction of movement. However, where fractures and joint patterns are developed and the permeability is high in a certain direction because of solution by ground water, the direction of flow may be quite different than the water-table map indicates.

The rate of movement of ground water is usually very slow. On the Edwards Plateau the hydraulic gradient may range from more than 50 feet per mile to less than 5 feet per mile. Normally, the slope of the water table increases nearer to the larger drainage ways.

When water moves very slowly all the molecules move in more or less parallel lines. This is described as streamline or laminar flow. As the velocity increases, a point is reached when laminar flow ceases and movement becomes turbulent. Flow that occurs between these two extremes is unstable. Flow in the Antlers Formation is laminar. The rate of movement may be from a few feet to several feet per year. Water moving through fractured or jointed rocks, or through solution channels, may attain much higher velocities and result in turbulent flow. Some of these rates could be on the order of several hundred feet per day.

The complexity of a limestone aquifer, coupled with an underlying aquifer of fine to coarse sand with extensive calcareous cementation and clay lenses, is almost impossible to describe in terms of direction of movement and rates of flow. Porosity in the limestone may change rapidly in either vertical or horizontal directions, and likewise, the permeability. Water-table conditions may extend for great distances or may occur in insolated areas. Rates of flow evidently increase toward the natural discharge points as the hydraulic gradient increases.

The direction of water movement in the alluvium aquifer is the same as in the streams. The rate of movement may be relatively fast compared to water moving in adjacent beds of the Antlers because of the higher permeabilities in the unconsolidated alluvial sediments.

The Hickory Sandstone Member of the Riley Formation extends radially away from the Llano uplift which centers in Llano and Mason Counties (Figure 7). Generally, the beds dip rather uniformaily at the rate of 100 to 150 feet per mile to the north, west, and southwest, and the piezometric surface of the Hickory should reflect the orientation of the beds. The hydraulic gradient would show less slope than the beds themselves, but the direction of ground water movement would normally be downdip. However, the altitude of the water surface in wells tapping the Hickory in McCulloch County (Mason, 1961, p. 28) shows the water to be moving more or less along the strike of the beds rather than downdip. An extension of the piezometric surface into adjoining areas would probably show the water movement to be downdip in the aquifer.

The description of the Hickory as a coarse to very fine-grained sandstone (Barnes and others, 1959, p. 26-27) indicates the rate of water movement should be very slow. Also, the altitude of the water surface indicates that the hydraulic gradient is about 5 to 10 feet per mile and not more than 20 feet per mile, well within the range for low-rate laminar flow. Another factor influencing the rate of flow in the Hickory aquifer is the temperature of the water. An increase in temperature of the water from 40°F (4°C) to 90°F (32°C) approximately doubles the velocity. Some of the usable water in the Hickory is encountered at depths greater than 3,000 feet below the land surface where the temperature is higher, thus the rate of flow is relatively higher than at shallower depths.

The direction in which the water moves through the Ellenburger-San Saba aquifer cannot accurately be determined because of the lack of data. The general direction of movement is believed to be away from the Llano uplift. The direction of movement of the ground water in the Lower Cretaceous aquifer is generally with the dip of the beds.

Natural Discharge of Ground Water

From the standpoint of volume of water discharged naturally, spring flow would rank first; then evapotranspiration from alluvium when the water table is near the surface along the main drainage ways. Ground-water loss due to interformational leakage or outflow cannot be determined because control is lacking.

Springs occur along the borders of the Plateau where erosion has cut the Edwards and associated limestones down to the water table. The major rivers formed by this erosional action are headed by springs. Following is a discussion of major springs that flow as headwaters of some of the streams on the Edwards Plateau.

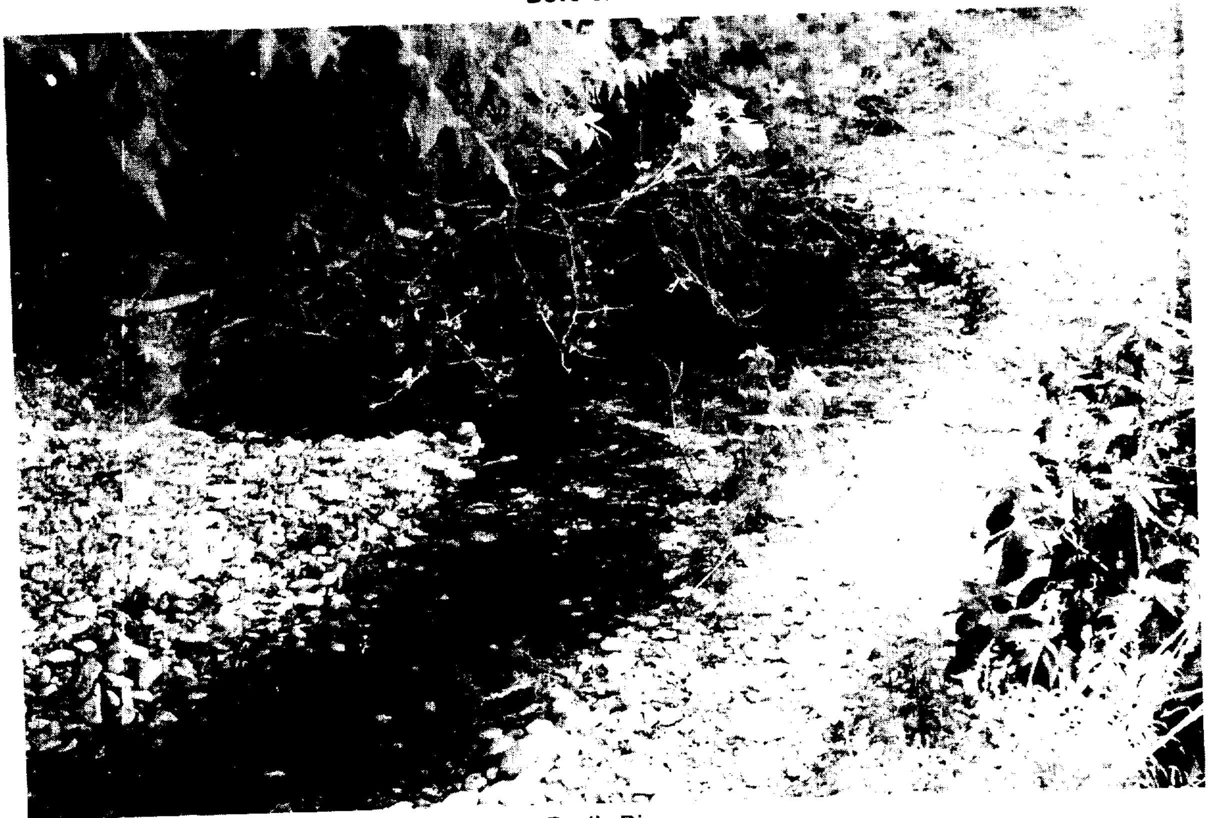
Spring Creek, Irion County-On the Reginald Atkinson Ranch near Mertzon, water issues from cracks in the limestone bed of the creek. According to Blank, and others (1966, p. 19), artesian pressure forces the water out and causes it to mound up about six inches. The estimated flow of the springs was 10 to 20 cubic feet per second (ft^3/s).

On a steep hillside, immediately above the springs, a friable dolomite which alternates with a dense, hard limestone, crops out. This suggests that the dolomite may be the aquifer within the Edwards and associated limestones. The approximate elevation of the springs is 2,200 feet above mean sea level.

Dove Creek, Irion County-On the Schreiner Ranch, 8 miles southeast of Mertzon, a large spring discharges from beneath thick, white limestone ledges. Approximately one-quarter of a mile downstream, dolomite beds overlying the white limestone can be seen. The springs appear to be located at the base of the dolomite beds. Artesian pressure is not evident. Estimates of the flow in August 1961, by Blank, and others (1966, p. 20) was about 20 ft^3/s. The altitude of the spring is about 2,162 feet above mean sea level.

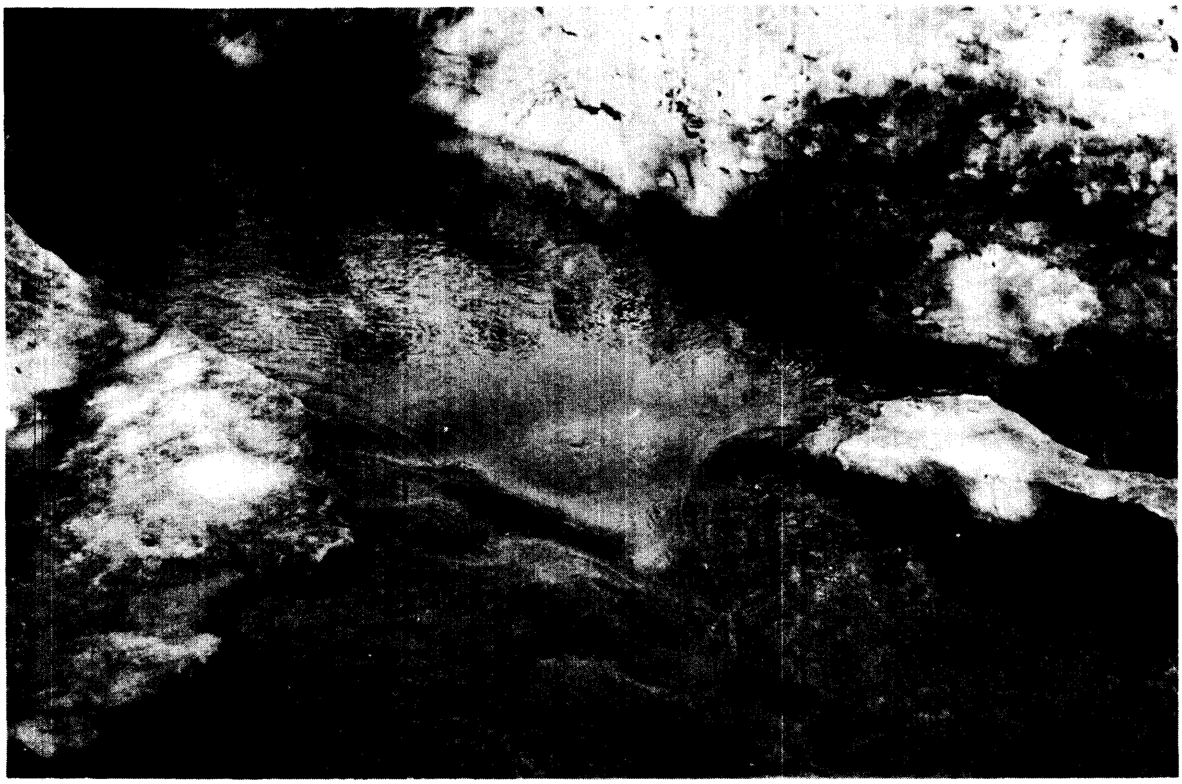
South ***Concho River, Tom Green Count***y-About 3 miles north of the Schleicher-Tom Green County line

Dove Creek



Devils River

on the Head-of-the-River Ranch, water flows from jointed white, flaggy limestone in the streambed of the South Concho River. It appears that the springs are located near the base of dolomite beds which appear just upstream. The approximate altitude of the springs is 2,071 feet above mean sea level.



South Concho River

San Saba River, Schleicher County.—About 1 mile west of the Schleicher-Menard County line, near Fort McKavett, springs issue from the bed of the San Saba River. One of the better sources of water is covered by a small rock house. The altitude at the springs is about 2,060 feet above mean sea level.

North Llano River, Sutton County.—At Fort Terrett in eastern Sutton County, water appears in the gravel streambed of the North Llano River on the Ray Parker Ranch. A spring fed pool of water is located a short distance upstream. A cliff, 60 to 75 feet high to the south of the upper pool, consists of beds of gray to dark gray dolomite and dolomitic limestone. The uppermost spring is about 1,972 feet above mean sea level.

South Llano River, Edwards County.—In the upper valley of the South Llano River, some of the largest springs on the interior of the Edwards Plateau issue from the Edwards and associated limestones. These springs, named Seven Hundred Springs, are located just south of the Edwards-Kimble County line near U.S. Highway 377. Water flows without evidence of artesian pressure. At the highway crossing, a thick stratum of dark gray, spongy dolomite crops out in the bed of the river. Measurements made in 1939 and 1955 showed flows from the springs ranging from 70 to 9,740 gallons per minute (gpm) along the South Llano River. From a point near the highway and downstream for several miles, springs occur between the elevations of about 1,950 to 1,890 feet above mean sea level.

Hackberry Creek, Edwards County.—Long (1962, p. 59) points out that on the Gilmer Ranch, 9 miles east of Rocksprings, there are springs that flowed 1,135 gpm in 1939 and 2,580 gpm in 1954. These springs issue from small openings beneath ledges of brownish-gray, spongy, fine-grained dolomite. The approximate elevation of these springs is 1,968 feet above mean sea level.

Nueces River, Real County.—On the Peterson Ranch, about 15 miles east of Rocksprings, flow of about 1 cfs appears from under ledges in the streambed. Flow increases from other springs farther downstream.

Frio River, Real County.—Water first appears in the bed of the Frio River on the Prade Ranch at an altitude of about 1,900 feet above mean sea level.

West Nueces River, Edwards County.—Kickapoo Springs head up the flow on the West Nueces River. These springs are located approximately 21 miles southwest of Rocksprings on the James Rudasill Ranch. There are several springs that flow from joints in the rock bed of the main stream; however, the largest spring flows from gravel under a small amount of artesian pressure. Long (1962, p. 76) measured a total flow of

Spring Creek

about 1,100 to 1,350 gpm. The altitude is about 1,748 feet above mean sea level.

Devils River, Val Verde County.—The uppermost springs on the Devils River are about 10 miles downstream from Juno. Flow issues from several openings along the base of a rock bluff on the west side of the valley (Blank, and others, 1966, p. 22). The springs are at an elevation of about 1,597 feet above mean sea level.

There are other springs farther south at lower elevations and on Dolan Creek about 1 mile above its mouth. The total flow from Dolan Springs and the many other complimentary springs was 3,100 gpm in 1939. The altitude at Dolan Springs is about 1,350 feet above mean sea level, considerably lower than Pecan Springs which is 17 miles to the northwest.

On the Edwards Plateau, an average of 285,686 acre-feet of water per year is estimated to be discharged from seeps and springs along streams as rejected recharge. A total of about 9,370 acre-feet per year is discharged by underflow on significant rivers.

The movement of water downdip in the Edwards and associated limestones in the vicinity of the Balcones fault zone is called subsurface outflow. The confinement by overlying impervious strata increases the artesian head as the water moves downdip. Eventually, this water is discharged at the land surface as artesian springs such as San Felipe Springs at Del Rio and Las Moras Springs near Brackettville. In Val Verde County alone, Reeves (1971) estimates that there is 500,000 acre-feet of water available for development that is discharged by springs.

Withdrawal of Ground Water by Wells

From 1955 through 1972, there has been approximately 1,260,000 acre-feet of ground water withdrawn from the Edwards-Trinity (Plateau) aquifer by municipal, industrial, irrigation, domestic, and livestock wells in the study area on the Edwards Plateau (Table 3). This is an average of about 70,000 acre-feet a year. In 1972, about 86,000 acre-feet or 76,600,000 gallons per day of water was withdrawn by wells on the Edwards Plateau.

Ector County and the city of Odessa pumped the greatest amount of water for municipal use with an average of about 3,300 acre-feet per year. Ector County also uses the most ground water annually for industrial and domestic purposes with an average of about 5,000 acre-feet and 670 acre-feet, respectively.

Most ground water is used for irrigation. Glasscock County leads all counties on the Edwards Plateau with an average of about 17,200 acre-feet per year, followed by Reagan County with about 8,500 acre-feet per year.

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72

(Amounts shown are in acre-feet)

Year	Water use: Public supply	Industrial	Irrigation	Domestic	Livestock
Bandera County					
1972	–	–	–	117.9	78.9
1971	–	–	–	118.6	79.7
1970	–	–	–	116.0	79.9
1969	–	0	–	119.1	80.8
1968	–	.1	–	114.8	74.4
1967	–	.1	–	110.7	85.8
1966	–	0	–	106.5	81.0
1965	–	.1	–	102.4	91.0
1964	–	.1	–	98.2	93.6
1963	–	.2	–	94.1	96.0
1962	–	.2	–	89.9	84.0
1961	–	0	–	85.8	100.8
1960	–	.1	–	81.7	103.2
1959	–	.1	–	83.5	105.6
1958	–	.1	–	85.2	103.6
1957	–	0	–	86.9	107.1
1956	–	0	–	88.7	108.0
1955	–	.1	–	90.5	108.7
Totals	–	1.2	–	1,790.5	1,662.1
Coke County					
1972	–	150.0	–	33.4	295.1
1971	–	152.7	–	33.4	296.2
1970	–	151.7	–	33.7	295.6
1969	–	152.9	–	34.2	295.9
1968	–	189.1	–	33.7	297.6
1967	–	215.5	–	33.2	301.7
1966	–	278.2	–	32.6	301.0
1965	–	336.6	–	32.2	302.8
1964	–	430.2	–	31.6	304.4
1963	–	402.2	–	31.0	309.2
1962	–	470.5	–	30.5	314.1
1961	–	2.3	–	30.0	315.2
1960	–	2.0	–	29.5	316.2
1959	–	3.1	–	30.4	325.9
1958	–	2.0	–	31.4	318.4
1957	–	3.6	–	32.3	310.6
1956	–	8.8	–	33.2	303.1
1955	–	4.1	–	34.2	295.5
Totals	–	2,955.5	–	580.5	5,498.5

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Public supply	Industrial	Irrigation	Domestic	Livestock
			Water use		
			Conchc County		
1972	227.6	1.0	–	93.7	194.0
1971	199.0	1.0	–	94.2	194.2
1970	180.0	1.0	–	94.6	194.6
1969	137.9	1.1	–	94.9	196.5
1968	120.6	1.2	–	91.3	197.6
1967	160.1	1.4	–	87.8	198.8
1966	149.3	2.4	–	84.2	199.9
1965	159.5	2.7	–	80.7	201.0
1964	173.9	3.1	–	77.1	202.0
1963	162.5	2.6	–	73.5	207.8
1962	172.1	3.8	–	70.0	213.7
1961	139.8	2.9	–	66.4	220.3
1960	162.2	2.2	–	62.8	225.2
1959	136.0	1.5	–	67.1	231.1
1958	135.5	.8	–	71.4	221.7
1957	126.0	1.6	–	75.6	212.5
1956	126.0	1.3	–	79.9	203.1
1955	119.7	1.5	–	84.1	194.0
Totals	2,787.7	33.1	–	1,449.3	3,708.0
			Crockett County		
1972	1,285.8	54.3	4,600.0	69.0	328.7
1971	1,105.0	172.7	4,580.0	69.0	329.4
1970	1,127.0	101.0	4,600.0	69.0	329.0
1969	1,006.8	81.1	4,539.0	67.2	329.7
1968	1,056.8	127.0	4,612.4	69.0	328.8
1967	1,257.9	144.0	4,946.5	70.8	328.1
1966	1,034.8	173.8	4,866.3	72.6	327.2
1965	1,143.8	132.3	4,999.2	74.4	326.4
1964	1,147.1	102.9	4,806.3	76.2	325.7
1963	1,077.4	257.9	4,492.2	77.9	323.6
1962	1,123.6	354.7	1,089.7	79.6	321.4
1961	943.3	247.1	1,247.3	81.4	319.3
1960	944.7	180.8	1,220.1	83.2	317.2
1959	934.8	264.8	1,319.1	85.7	315.2
1958	815.1	237.6	1,233.7	88.0	310.8
1957	836.3	242.5	1,171.2	90.5	306.4
1956	919.5	307.4	1,144.8	93.0	302.3
1955	700.0	326.5	1,291.8	95.4	297.7
Totals	18,459.7	3,508.4	56,759.6	1,411.9	5,766.9

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use: Public supply	Industrial	Irrigation	Domestic	Livestock
			Ector County		
1972	1,617.9	4,627.1	550.0	750.0	16.7
1971	1,700.0	5,751.5	573.0	749.9	16.7
1970	1,717.0	5,316.0	560.0	753.8	17.0
1969	1,468.2	6,316.5	624.1	753.8	17.0
1968	990.2	5,351.0	539.9	729.8	16.4
1967	1,544.0	5,676.4	539.9	705.8	15.6
1966	1,184.1	5,668.2	539.9	682.0	15.2
1965	1,920.0	5,640.4	539.9	658.0	14.2
1964	1,748.0	5,194.0	470.8	634.0	13.4
1963	1,293.2	5,347.0	470.8	610.0	13.6
1962	1,564.7	5,132.1	470.8	586.0	13.8
1961	3,175.9	5,180.8	470.8	562.0	13.4
1960	2,410.3	4,614.2	417.7	538.2	13.6
1959	3,744.0	4,524.5	282.5	585.4	13.2
1958	7,005.5	4,240.7	195.3	632.6	13.8
1957	9,401.1	4,168.0	195.3	680.0	14.0
1956	9,377.5	3,727.2	195.3	727.2	14.4
1955	7,902.0	3,653.0	144.2	774.4	14.8
Totals	59,763.6	90,128.6	7,780.2	12,112.9	266.8
			Edwards County		
1972	559.8	5.0	–	146.8	707.8
1971	244.0	6.3	–	147.2	709.0
1970	296.0	5.9	–	147.0	709.0
1969	181.3	8.7	–	147.2	709.4
1968	220.9	3.1	–	144.4	687.8
1967	331.4	.8	–	141.7	663.2
1966	331.4	1.5	–	138.9	638.4
1965	220.9	5.2	–	136.1	613.7
1964	199.4	8.3	–	133.3	589.0
1963	200.2	2.1	–	130.5	602.3
1962	199.6	.4	–	127.8	615.4
1961	204.0	4.1	–	125.0	628.6
1960	184.1	2.1	–	122.2	641.9
1959	186.8	1.0	–	125.8	655.1
1958	167.2	.8	–	129.5	663.3
1957	120.9	1.5	–	133.1	671.7
1956	120.9	8.7	–	136.8	680.2
1955	120.9	.4	–	140.4	688.5
Totals	4,089.7	65.9	–	2,453.7	11,874.3

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Public supply	Industrial	Irrigation	Domestic	Livestock
			Gillespie County		
1972	–	–	320.0	342.9	358.9
1971	–	–	322.8	343.0	359.0
1970	–	–	323.0	343.6	359.0
1969	–	–	323.0	343.9	359.6
1968	–	–	323.0	336.8	355.0
1967	–	–	323.0	329.8	350.7
1966	–	–	323.0	322.7	346.4
1965	–	–	323.0	315.8	341.9
1964	–	–	323.0	308.7	337.5
1963	–	–	323.0	301.6	340.1
1962	–	–	323.0	294.6	342.6
1961	–	–	323.0	287.5	345.2
1960	–	–	323.0	280.5	347.9
1959	–	–	323.0	287.0	350.5
1958	–	–	323.0	293.4	346.1
1957	–	–	323.0	299.9	341.9
1956	–	–	323.0	306.2	337.4
1955	–	–	320.0	312.7	333.1
Totals	–	–	5,807.8	5,650.6	6,252.8
			Glasscock County		
1972	–	4.7	23,701.0	100.8	244.6
1971	–	5.3	22,860.0	100.8	245.0
1970	–	5.6	27,108.9	101.0	245.6
1969	–	5.8	26,910.8	101.9	248.0
1968	–	12.2	30,257.7	101.0	230.8
1967	–	12.7	23,712.7	100.1	212.9
1966	–	20.4	22,799.8	99.2	196.5
1965	–	11.0	20,791.5	98.4	179.3
1964	–	7.2	22,749.3	97.3	162.2
1963	–	9.6	17,606.2	96.4	158.8
1962	–	8.3	16,642.3	95.5	155.3
1961	–	8.7	14,024.3	94.7	152.1
1960	–	4.5	10,798.5	93.8	148.6
1959	–	3.1	8,006.1	93.4	145.2
1958	–	3.2	6,196.7	93.2	139.6
1957	–	6.6	6,631.0	93.0	134.1
1956	–	16.3	5,776.9	92.7	128.5
1955	–	10.8	4,009.2	91.0	122.8
Totals	–	156.0	310,582.9	1,744.2	3,249.9

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use				
	Public supply	Industrial	Irrigation	Domestic	Livestock
		Howard County			
1972	294.9	1.6	–	51.7	33.0
1971	287.0	2.3	–	52.8	33.0
1970	181.0	2.0	–	52.9	33.0
1969	252.1	3.9	–	53.7	33.3
1968	174.8	4.6	–	61.5	33.2
1967	208.3	5.2	–	69.2	30.0
1966	160.0	5.2	–	77.1	33.3
1965	161.6	5.3	–	84.8	33.3
1964	184.9	5.8	–	92.6	33.3
1963	193.9	5.3	–	100.5	32.1
1962	219.3	4.9	–	108.2	30.9
1961	34.8	5.3	–	116.0	29.8
1960	34.7	4.8	–	123.8	28.6
1959	35.7	8.0	–	124.6	27.4
1958	33.6	6.6	–	125.2	27.2
1957	28.0	8.1	–	126.0	27.0
1956	16.5	6.6	–	126.7	26.8
1955	16.5	7.8	–	127.5	26.8
Totals	2,517.6	93.3	–	1,674.8	552.0
		Irion County			
1972	10.2	20.9	769.0	83.8	254.3
1971	7.0	24.7	769.9	84.5	255.0
1970	9.0	18.0	770.8	84.5	255.0
1969	42.6	147.0	782.0	84.9	256.1
1968	38.7	151.3	771.8	85.6	251.7
1967	34.9	132.8	799.4	86.4	247.3
1966	30.5	125.2	806.9	87.0	242.9
1965	38.7	101.6	817.4	87.7	238.6
1964	34.3	85.5	330.6	88.5	234.3
1963	35.5	85.0	12.8	89.2	237.1
1962	34.5	84.6	11.0	89.8	239.8
1961	31.9	6.5	11.7	90.5	242.5
1960	33.3	10.6	7.6	91.3	245.2
1959	34.0	12.2	3.0	94.8	248.0
1958	34.1	8.8	2.5	98.1	240.9
1957	33.5	19.4	2.5	101.6	234.1
1956	33.5	19.1	9.3	105.1	227.1
1955	35.4	10.1	–	108.5	220.4
Totals	551.6	1,064.0	6,678.2	1,641.8	4,370.3

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use				
	Public supply	Industrial	Irrigation	Domestic	Livestock
Kerr County					
1972	–	10.0	–	674.6	300.0
1971	–	11.2	–	674.0	300.9
1970	–	–	–	673.6	300.9
1969	–	–	–	673.6	301.9
1968	–	1.0	–	671.7	307.1
1967	–	1.0	–	669.8	312.4
1966	–	0	–	667.9	317.7
1965	–	0	–	666.0	323.0
1964	–	.2	–	630.5	328.3
1963	–	.2	–	662.2	334.8
1962	–	0	–	660.2	341.4
1961	–	.3	–	658.4	348.1
1960	–	.3	–	656.5	354.6
1959	–	.2	–	653.2	361.3
1958	–	.3	–	639.1	361.1
1957	–	0	–	625.1	361.0
1956	–	0	–	610.9	360.8
1955	–	0	–	596.8	360.7
Totals	–	24.7	–	11,764.1	5,976.0
Kimble County					
1972	–	45.5	–	157.0	231.8
1971	–	45.4	–	157.0	232.1
1970	–	31.0	–	157.6	232.0
1969	–	.7	–	157.8	232.2
1968	–	.3	–	154.7	232.3
1967	–	.3	–	151.7	232.1
1966	–	.7	–	148.6	232.1
1965	–	0	–	145.6	231.9
1964	–	2.5	–	142.5	231.9
1963	–	.8	–	139.5	236.9
1962	–	2.0	–	136.4	241.7
1961	–	1.8	–	133.3	246.7
1960	–	1.7	–	130.3	251.7
1959	–	1.3	–	172.2	256.5
1958	–	.8	–	213.9	257.2
1957	–	.7	–	255.8	257.9
1956	–	1.0	–	297.7	258.3
1955	–	1.5	–	339.6	259.0
Totals	–	138.0	–	3,191.2	4,354.3

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use				
	Public supply	Industrial	Irrigation	Domestic	Livestock
		Kinney County			
1972	–	–	–	31.8	142.7
1971	–	–	–	32.9	142.7
1970	–	–	–	32.9	142.7
1969	–	0.1	–	33.0	143.2
1968	–	0	–	32.8	138.2
1967	–	.2	–	32.5	140.4
1966	–	.2	–	32.3	143.0
1965	–	.1	–	31.9	145.0
1964	–	.1	–	31.6	147.3
1963	–	.2	–	31.4	152.5
1962	–	.6	–	31.0	157.6
1961	–	.5	–	30.8	162.8
1960	–	.4	–	30.5	167.9
1959	–	.1	–	37.8	173.0
1958	–	.2	–	44.9	165.0
1957	–	.2	–	52.2	157.0
1956	–	.1	–	59.4	149.0
1955	–	.1	–	66.7	140.9
Totals	–	3.1	–	676.4	2,710.9
		McCulloch County			
1972	–	1.0	–	63.7	132.0
1971	–	.8	–	64.0	132.0
1970	–	.7	–	64.0	132.9
1969	–	0	–	64.3	133.7
1968	–	.2	–	63.4	132.8
1967	–	.2	–	62.5	131.7
1966	–	0	–	61.6	130.4
1965	–	0	–	60.7	129.6
1964	–	.5	–	59.8	128.6
1963	–	.1	–	58.9	128.4
1962	–	.5	–	58.0	128.4
1961	–	.5	–	57.1	128.2
1960	–	.5	–	56.2	128.1
1959	–	.5	–	61.8	128.0
1958	–	.5	–	67.3	124.0
1957	–	1.3	–	72.9	120.3
1956	–	1.1	–	78.4	116.4
1955	–	1.2	–	84.0	112.6
Totals	–	9.6	–	1,158.6	2,298.1

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use				
	Public supply	Industrial	Irrigation	Domestic	Livestock
			Menard County		
1972	313.4	3.2	460.0	87.6	357.0
1971	276.0	3.5	461.3	86.7	359.6
1970	186.0	3.7	460.1	87.0	368.7
1969	189.3	4.0	463.3	87.5	369.8
1968	191.9	4.8	463.4	87.8	361.9
1967	271.6	4.2	461.8	88.2	354.1
1966	252.0	2.5	461.8	88.6	346.3
1965	234.8	2.7	464.1	88.9	334.8
1964	263.6	5.3	466.3	89.3	330.7
1963	280.4	9.3	462.3	89.6	336.9
1962	177.3	9.9	463.3	89.9	343.0
1961	237.3	7.4	466.6	90.4	349.2
1960	263.6	5.0	468.3	90.7	355.2
1959	253.5	2.5	296.2	94.3	361.4
1958	169.9	2.3	4.9	97.9	346.9
1957	153.0	.8	7.0	101.6	332.5
1956	233.5	.6	2.6	105.2	317.9
1955	203.9	.6	–	108.8	303.4
Totals	4,151.0	72.3	6,333.3	1,660.0	6,229.3
			Midland County		
1972	183.8	311.6	2,608.0	57.8	121.6
1971	189.0	637.2	2,590.0	57.5	120.0
1970	143.0	1,238.0	2,610.8	57.6	120.6
1969	140.0	1,220.4	2,605.2	57.2	121.8
1968	139.0	1,862.5	2,624.2	67.1	117.4
1967	139.0	2,140.2	2,646.7	77.0	112.9
1966	135.0	2,080.3	2,715.7	86.7	108.5
1965	135.0	1,087.1	2,391.3	96.6	104.0
1964	133.0	823.8	2,259.8	106.4	99.6
1963	132.0	738.1	1,804.3	116.3	98.0
1962	130.0	820.6	1,522.8	126.1	96.3
1961	130.0	804.9	1,436.7	135.9	94.7
1960	125.0	668.1	1,226.7	145.8	92.9
1959	125.0	614.9	746.0	144.6	91.3
1958	124.0	657.0	737.1	143.4	93.7
1957	121.0	558.7	610.8	142.2	96.1
1956	120.0	627.6	381.2	140.9	98.5
1955	120.0	627.2	396.3	139.8	100.8
Totals	2,463.8	17,518.2	31,913.6	1,898.9	1,888.7

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use				
	Public supply	Industrial	Irrigation	Domestic	Livestock
			Reagan County		
1972	449.6	1,062.8	12,902.3	44.9	211.7
1971	451.3	1,690.6	12,911.0	45.3	212.9
1970	433.0	1,670.0	13,644.1	45.0	212.7
1969	498.7	1,661.9	13,855.4	45.3	214.9
1968	516.7	1,638.9	12,686.1	47.0	216.1
1967	541.8	1,962.8	12,578.9	49.0	217.2
1966	503.2	2,036.9	12,720.4	50.7	218.5
1965	495.8	1,315.1	11,848.5	52.5	219.8
1964	514.8	1,082.1	12,884.1	54.4	221.0
1963	522.1	1,154.5	10,273.8	56.2	209.4
1962	470.9	1,198.1	6,782.2	58.0	197.9
1961	406.2	1,425.8	4,658.9	59.8	186.2
1960	463.0	1,771.1	4,025.9	64.7	174.6
1959	443.9	1,555.1	3,484.9	63.7	163.2
1958	550.0	900.1	2,046.7	62.7	146.1
1957	651.0	670.1	2,042.6	61.8	129.0
1956	709.3	679.7	1,889.7	60.8	111.9
1955	571.0	228.9	1,261.7	59.8	95.0
Totals	9,192.3	23,771.1	152,497.2	981.6	3,358.1
			Real County		
1972	–	–	–	71.8	284.4
1971	–	–	–	72.3	285.3
1970	–	–	–	72.6	285.0
1969	–	–	–	73.3	289.0
1968	–	–	–	71.7	274.1
1967	–	–	–	70.1	259.2
1966	–	–	–	68.6	244.2
1965	–	–	–	67.0	229.3
1964	–	–	–	65.4	214.3
1963	–	–	–	63.9	215.0
1962	–	–	–	62.3	215.8
1961	–	0.4	–	60.7	216.6
1960	–	–	–	59.1	217.4
1959	–	–	–	64.3	218.2
1958	–	–	–	69.5	215.6
1957	–	–	–	74.7	213.0
1956	–	–	–	79.9	210.2
1955	–	–	–	85.1	207.6
Totals	–	0.4	–	1,252.3	4,294.2

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use: Public supply	Industrial	Irrigation	Domestic	Livestock
			Schleicher County		
1972	250.6	4.0	6,206.3	92.9	200.0
1971	210.3	208.1	6,210.9	92.9	200.6
1970	204.0	76.0	6,070.3	93.4	200.6
1969	206.8	166.8	6,062.3	93.2	201.5
1968	237.3	204.4	6,025.4	95.0	216.5
1967	187.5	131.8	7,009.8	96.8	210.7
1966	224.0	131.4	6,445.7	99.2	204.8
1965	201.0	131.3	6,197.8	100.4	198.8
1964	224.3	154.6	6,429.7	102.2	194.1
1963	223.1	116.0	5,344.4	104.0	198.9
1962	204.0	125.8	4,478.7	105.7	205.2
1961	206.8	117.4	4,360.5	107.5	211.3
1960	205.7	93.5	4,375.3	109.3	217.6
1959	205.5	52.3	3,929.7	111.7	223.7
1958	231.5	152.6	3,646.2	114.1	225.7
1957	260.8	10.7	3,326.3	116.5	227.0
1956	334.5	11.4	2,861.9	118.8	228.9
1955	406.7	10.5	1,646.4	121.3	230.6
Totals	4,224.4	1,898.6	90,627.6	1,874.9	3,796.5
			Sterling County		
1972	190.4	237.7	1,710.6	15.3	52.0
1971	78.9	247.3	1,710.6	15.4	52.5
1970	71.0	235.0	1,718.3	14.9	52.8
1969	60.0	315.0	1,715.4	14.7	53.7
1968	60.0	335.1	1,948.4	15.7	52.3
1967	60.0	406.0	1,606.5	16.7	50.8
1966	60.0	442.0	1,586.5	17.7	49.3
1965	60.0	315.7	1,387.8	18.7	47.9
1964	56.0	424.9	997.0	19.8	46.3
1963	56.0	390.2	945.7	20.8	47.9
1962	55.0	487.3	445.8	21.8	49.6
1961	45.0	674.1	434.3	22.9	51.2
1960	45.0	732.4	444.5	23.9	52.8
1959	45.0	558.2	437.5	25.0	54.3
1958	45.0	258.8	439.4	26.2	55.2
1957	40.0	4.2	434.3	27.3	55.8
1956	40.0	7.2	434.3	28.6	56.8
1955	40.0	10.9	434.3	29.7	57.6
Totals	1,107.3	6,082.0	18,831.2	375.1	938.8

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use: Public supply	Industrial	Irrigation	Domestic	Livestock
			Sutton County		
1972	715.8	18.7	2,000.3	148.0	770.9
1971	696.3	12.1	2,000.1	148.8	773.1
1970	843.0	7.0	1,980.6	149.1	773.0
1969	558.1	9.7	2,111.4	149.0	774.0
1968	566.2	12.5	1,992.0	146.3	758.4
1967	723.8	17.9	1,218.3	143.7	742.9
1966	618.1	22.2	2,286.6	141.0	727.3
1965	665.1	21.8	2,704.4	138.4	711.8
1964	662.2	28.4	1,589.6	135.9	696.1
1963	729.2	18.8	888.7	133.2	702.5
1962	711.7	19.2	882.6	130.6	708.9
1961	604.0	14.9	712.2	127.9	715.3
1960	654.2	.6	288.8	125.3	721.7
1959	435.7	18.3	691.4	125.2	728.1
1958	435.7	7.1	691.5	125.1	695.3
1957	336.0	3.4	414.2	125.1	662.3
1956	336.0	4.5	97.2	125.0	629.3
1955	336.0	5.8	146.6	125.0	596.1
Totals	10,627.1	242.9	22,696.5	2,442.6	12,887.0
			Tom Green County		
1972	71.2	23.0	1,045.8	68.0	309.8
1971	–	16.1	1,045.8	68.0	310.3
1970	22.1	2.0	1,045.8	68.3	310.9
1969	–	2.4	1,045.8	68.6	313.8
1968	–	3.7	1,045.8	66.5	303.0
1967	–	3.9	1,045.8	64.7	292.0
1966	–	7.6	1,045.8	62.9	281.2
1965	–	8.2	1,045.8	61.1	270.4
1964	–	6.9	1,045.8	59.3	259.4
1963	–	41.7	1,045.8	57.5	271.6
1962	–	38.9	1,045.8	55.7	277.7
1961	–	5.9	1,045.8	53.9	286.8
1960	–	6.8	1,045.8	52.1	296.0
1959	–	3.9	1,045.8	55.5	305.2
1958	–	5.1	1,045.8	58.9	289.6
1957	–	8.8	1,045.8	62.3	273.9
1956	–	12.1	204.4	65.7	258.1
1955	–	10.9	–	69.1	242.4
Totals	93.3	207.9	16,937.2	1,118.1	5,152.1

Table 3.—Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72—Continued

(Amounts shown are in acre-feet)

Year	Water use: Public supply	Industrial	Irrigation	Domestic	Livestock
			Upton County		
1972	260.7	123.7	4,506.3	108.1	76.3
1971	224.0	195.3	4,800.1	108.1	76.8
1970	314.0	234.0	4,780.3	108.2	77.3
1969	405.5	1,376.3	4,850.0	107.3	77.7
1968	231.7	1,166.7	4,629.8	109.8	75.9
1967	214.8	991.0	4,625.0	112.2	74.2
1966	196.1	653.8	4,396.5	114.7	72.7
1965	150.3	354.6	4,325.7	117.2	71.0
1964	154.2	1,059.7	3,235.6	119.6	69.3
1963	135.0	1,051.4	2,704.4	122.0	75.7
1962	135.0	617.5	1,745.7	124.0	82.1
1961	135.0	328.5	1,566.0	126.9	88.5
1960	135.0	446.5	846.5	129.4	95.0
1959	154.2	547.8	816.2	124.7	101.3
1958	154.2	494.7	707.2	120.0	102.8
1957	153.4	326.8	459.9	115.2	103.5
1956	156.5	553.3	459.9	110.4	104.7
1955	161.7	534.9	459.9	105.7	105.9
Totals	3,471.3	11,056.5	49,915.0	2,083.5	1,530.7
			Uvalde County		
1972	—	6.0	—	224.0	524.7
1971	—	6.1	—	223.8	525.4
1970	—	6.0	—	223.8	525.8
1969	—	5.8	—	224.0	526.2
1968	—	3.7	—	229.1	526.7
1967	—	1.0	—	234.2	526.6
1966	—	.2	—	239.3	526.6
1965	—	.7	—	244.3	526.5
1964	—	.1	—	249.4	526.3
1963	—	.2	—	254.5	518.0
1962	—	.1	—	259.5	508.6
1961	—	.1	—	264.7	505.0
1960	—	.2	—	269.7	492.8
1959	—	0	—	302.9	486.3
1958	—	0	—	336.0	488.2
1957	—	—	—	369.2	490.1
1956	—	0	—	402.3	491.9
1955	—	—	—	435.5	493.8
Totals	—	30.2	—	4,986.2	9,209.5

Table 3.-Total Estimated Pumpage From the Edwards-Trinity (Plateau) Aquifer, 1955-72-Continued

(Amounts shown are in acre-feet)

Year	Water use: Public supply	Industrial	Irrigation	Domestic	Livestock	Total of all water use by year
			Val Verde County			
1972	48.5	50.2	530.6	336.4	457.2	85,808.4
1971	51.o	50.0	575.8	336.4	459.0	87,047.2
1970	44.0	94.0	600.0	336.8	459.3	91,935.3
1969	40.1	2.1	617.0	336.7	460.1	93,902.0
1968	34.4	.6	505.4	360.4	459.1	94,710.5
1967	42.7	1.4	678.4	384.1	460.9	90,302.2
1966	29.6	.6	566.1	407.8	461.8	88,559.0
1965	18.1	1.4	610.7	431.5	461.5	83,864.4
1964	16.6	3.3	627.0	455.2	461.8	83,365.9
1963	18.1	2.9	630.3	478.9	483.6	72.023.9
1962	14.6	9.6	620.6	502.6	505.2	61,510.3
1961	7.5	.8	553.8	526.3	526.7	56,934.7
1960	9.5	2.7	543.6	550.3	548.4	50,814.8
1959	-	3.3	572.0	515.4	570.1	47,633.3
1958	-	2.3	490.5	480.7	568.4	45,412.1
1957	–	1.9	543.3	446.1	569.4	46,282.8
1956	–	4.2	734.4	411.3	569.1	43,814.3
1955	–	1.9	615.5	376.6	568.8	37.688.3
Totals	374.7	233.2	10,615.9	7,673.5	9,050.4	
Total of all water use for the l&year period, 1955-72.						1,261,609.4

Most of the pumpage in these two counties is localized in the St. Lawrence area of south central Glasscock County and north central Reagan County. Another area on the Plateau where irrigation pumpage is relatively concentrated is in western Schleicher County where approximately 5,000 acre-feet is pumped annually.

Wells in Sutton County pumped the most water for livestock use with an average of about 700 acre-feet per year.

Hydraulic Characteristics of Aquifers

The factors that influence the manner in which ground water is yielded to a pumping well are called the hydraulic characteristics of the aquifer or water-bearing formation. These characteristics include the porosity, permeability, coefficient of transmissibility, coefficient of storage, specific yield, and specific capacity.

Porosity and Permeability

The physical property that defines the degree to which a rock contains interstices or void spaces that may be filled with fluid or gas is called porosity. It is quantitatively expressed as a percentage of the total volume of the rock. In pervious sedimentary rocks such as sandstone, the porosity is determined by the interrelationship of size, shape, sorting, nature of the matrix, and degree of cementation; whereas, porosity in soluble limestones depends upon size, shape, and pattern of fractures, and the relative purity of the limestones. Pure limestones will dissolve more easily than impure ones. Solution channels are developed in limestones by ground water along fractures such as faults and joints. Vugular limestones are developed by dissolving the material from between fossils. This commonly occurs in fossiliferous rudistid limestones of the lower Edwards Formation. In dense sedimentary, igneous, or metamorphic rocks, porosity depends upon the size, shape, and pattern of fracturing. Porosities may range from zero to greater than 50 percent, depending upon the nature of the sedimentary material.

Listed below are representative ranges of porosity accord ng to Todd (1959, p. 16).

Material	Porosity (percent)
Soils	50-60
Clay	45-55
Silt	40 50
Medium to coarse, mixed sand	35-40
Uniform sand	30 40
Fine to medium, mixed sand	30-35
Gravel and sand	20-35
Sandstone	10 20
Shale	1 10

Permeability is the capacity of a rock to transmit a fluid. It is measured by the coefficient of permeability which is defined as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot, under a hydraulic gradient of 1 foot per foot, and at a temperature of 60°F (16°C). Symbolically this is expressed as gallons per day per square foot (gpd/ft^2). Permeability is related to the number and size of the void spaces in the rocks and also to the degree of interconnection of the void spaces. Granular materials have permeabilities that vary with the diameter and degree of assortment of individual particles. A well-sorted coarse sand has a lower permeability than a well-sorted gravel. However, gravel with a moderate percentage of medium- and fine-grained material may be considerably less permeable than a uniformly-sized coarse sand.

Pumping tests of wells on the Edwards Plateau have indicated coefficients of permeability in the Antlers Formation ranging from 13 gpd/ft^2 (well YL-44-49-209) to 38 gpd/ft^2 (well Y L-45-23-702).

Measurement of permeability in the Edwards and associated limestones is almost impossible due to the variation in porosity caused by solution channels, cracks, and vugs.

Coefficients of Transmissibility and Storage

The coefficient of transmissibility is the rate of flow of ground water at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent. The coefficient of transmissibility is the product of the coefficient of permeability and aquifer thickness, and is expressed as gallons per clay per foot (gpd/ft). Determination of the volume of water that will flow through each foot of the aquifer is the product of the hydraulic gradient and the coefficient of transmissibility. For the flow to remain constant, small coefficients of transmissibility require greater hydraulic gradients.

The results of pumping tests were analyzed by either the nonequilibrium formula or by the recovery formula (Theis, 1935) and are listed in Table 4. The range in coefficients of transmissibility was from 1,100 to 6,573 gpd/ft. Calculated from all tests, the average coefficient of transmissibility was 2,728 gpd/ft.

Variations in the coefficient of transmissibility may be caused by either natural characteristics of the aquifer or by the properties of the discharging well. One of the natural characteristics could be the heterogeneity of the aquifer or lack of uniformity of the sediments. For example, the Antlers was deposited by an advancing sea that reworked sediments from the underlying terrain it crossed. This resulted in a conglomeration of sandstones, gravel, and shales within the formation. Shale lenses intermingled with the sandstones alter the water-producing zones for any well penetrating such a section, therefore, influencing the coefficient of transmissibility. Also, the degree of cementation would determine, to some extent, the effective porosity and permeablity of the water-bearing formation and, in turn, would affect the coefficient at transmissibility.

Properties of a discharging well that can influence the coefficient of transmissibility are partial penetration of the aquifer, degree of well development at the time of completion, effective well diameter, encrustation of casing or well screen, effective surface area exposed to water-producing zones, and the type of gravel packing.

The effective well diameter is not necessarily the slotted casing or well screen diameter. For instance, if the well is highly developed, the effective diameter may be substantially larger than the casing or screen diameter. Faulty construction or caving may cause a decrease in effective well diameter.

Well deterioration may be caused by encrustation on slotted casing or screens that would result in a lower coefficient of transmissibility. In addition, the finer particles adjacent to the well bore may migrate inward and begin to restrict the flow of water; hence, lowering the coefficient of transmissibility.

From the foregoing, it can be deduced that decreasing coefficients of transmissibility may not be caused entirely by declining water levels, but also by deteriorating well conditions adjacent to the producing zones. This explains, in part, decreasing well efficiencies.

The coefficient of storage is a measure of the volume of water available for withdrawal and is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Under water-table conditions, the coefficient of storage is practically equal to the specific yield. The quantity of water released by gravity drainage from the saturated zone of a water-bearing formation is the specific yield expressed as a percentage of the total saturated volume.

The coefficient of storage for the Antlers Formation is 0.074, which is an average of all storage coefficients obtatned. It is difficult to determine the storage of the Edwards and associated limestones because of the difficulty in obtaining an accurate measurement of the porosity.

Yields of Wells

While performing power-yield tests on the Edwards-Trinity (Plateau) aquifer throughout the Edwards Plateau, yields were determined on 168 irrigation and municipal wells. The high, low, and average yields for 160 of these tests are shown in the following table.

County	Yields (gpm) High	Low	Average	Number of tests
Concho	46.7	–	46.7	1
Crockett	392.3	159.5	242.1	5
Glasscock	1.541.5	59.1	95.8	97
Irion	668.0	153.4	410.7	3
Midland	162.3	50.0	99.5	3
Reagan	185.7	27.8	88.7	33
Schleicher	216.7	144.5	354.6	8
Sutton	668.0	44.4	353.1	4
Upton	272.8	72.0	171.5	6

The largest yield of 1,541 gpm is shown in Glasscock County on the Steve Currie Ranch from well KL-44-14-203. The low yield of 28 gpm was from well UZ-44-28-908 in Reagan County. The high average was 411 gpm in Irion County and the low was 47 in Concho County. However, it must be noted that the number of tests were 3 and 1, respectively, and therefore these

Table 4.—Hydraulic Characteristics of the Antlers Aquifer

Well	Date	Producing interval (feet)	Coefficient of transmissibility (gpd/ft)	Coefficient of permeability (gpd/ft²)	Coefficient of storage	Yield (gpm)	Specific capacity (gpm/ft)	Remarks
				REAGAN COUNTY				
UZ-44-28-902	May 19, 1966	185-435	2,808	—	—	383	8.0	Drawdown test.
29-910	May 18, 1966	185-511	3,250	—	—	122	2.7	Do.
902	do	—	6,573	—	0.0423	—	—	Interference test: Well UZ-44-29-910 was pumping 122 gpm.
36-303	May 5, 1966	229-287 305-326	2,464	—	—	56	.85	Drawdown test.
				UPTON COUNTY				
YL-44-41-907	Sept. 3, 1966	80-210	1,400	14	—	—	—	Interference test: Well YL-44-41-905 was pumping 23 gpm.[1]
49-209	Nov. 29, 1965	20-170	—	13	—	36	—	Recovery test.[1]
45-23-701	Dec. 8, 1965	140-148 195-218	1,100	32	—	53	—	Do.
702	do	40-210	1,500	38	—	—	—	Interference test: Well TJ-45-23-701 was pumping 52.6 gpm.[1]
				MIDLAND COUNTY				
TJ-44-18-200	1971	—	—	—	0.148	—	—	Preston-Shackelford water-well field.[2]
45-07-417	1948	—	10,000	—	—	170	2.200	3
23-909	1959	—	—	—	—	—	.455	—
910	do	—	—	—	—	—	.257	—
911	do	—	—	—	—	—	1.810	—
912	do	—	—	—	—	—	.273	—
913	do	—	—	—	—	—	1.430	—
914	do	—	—	—	—	—	.667	—
				GLASSCOCK COUNTY				
—	1971	—	—	—	0.0673	—	—	St. Lawrence area.[2]
				STERLING COUNTY				
XP-43-02-700	—	—	—	—	0.0387	—	—	Union-Texas water-well field.[2]

[1] From White, 1968.
[2] Coefficient of storage was determined from volume of dewatered area and volume of water pumped.
[3] From Meyers, 1969.

results are not considered very accurate. Results obtained in Glasscock and Reagan would be more accurate since more tests were performed.

Specific Capacities of Wells

The specific capacity is a function of several factors. The yield of a well in gallons per minute per foot (gpm/ft) of drawdown depends upon the effective diameter of the well, the depth penetrated into the aquifer, the type of perforations in the casing, and the extent to which the well was developed. The following table shows specific capacities determined from power-yield data obtained during this study.

County	Specific capacity (gpm/ft)			Number of tests
	High	Low	Average	
Crockett	9.56	–	9.56	1
Glasscock	3.10	0.17	1.19	27
Midland	0.87	.83	0.85	2
Reagan	2.77	.52	1.17	12
Schleicher	8.40	1.10	4.40	3
Sterling	22.30	1.70	9.19	4
Upton	1.40	.49	.94	2

The more accurate specific capacities shown in the table would probably be in Crockett or Schleicher Counties where open hole wells penetrate the Edwards and associated limestones. Hence, the effect on the well should be at minimum since there is no perforated casing or screens. Specific capacities of wells that have perforated casings are likely to be low because of well deterioration, perforated casing completion, and general overall inefficiency of the well. Pumping levels measured in the casings fall much lower than the pumping levels in the aquifers. Such losses of head result in lower specific capacities and, consequently, lower coefficients of transmissibility.

DEVELOPMENT OF THE EDWARDS-TRINITY (PLATEAU) AQUIFER

The first development of ground water on the Edwards Plateau supplied U.S. Army forts and stagecoach stops where spring and stream supplies were not available. A shallow well was developed in 1852 at Fort McKavett in western Menard County. Other wells were developed during the middle to late 1800's along the Butterfield Stage route which traversed the northern part of the Edwards Plateau.

Development of ground water for livestock and rural domestic use began about 1880 with the introduction of the windmill in the West Texas area. The earliest record of wells developed for public supply on the Edwards Plateau was at Big Spring in Howard County in 1925. Many small towns and communities located on the Edwards Plateau obtain public or private water supplies from the Edwards-Trinity (Plateau) aquifer.

Water from most of the earlier wells developed for industrial purposes during 1920-30 was used to supply water for drilling oil and gas tests and making ice, while later uses were for gasoline plants, refineries, and industrial complexes.

Development of ground water for irrigation began about 1946. The use of water for this purpose developed slowly until about 1960 when the number of wells drilled for irrigation increased rapidly in counties in the northwestern part of the Plateau. From 1946 to 1959, 40 wells were drilled for irrigation use in Glasscock County, and 161 wells were developed from 1960 to 1966. Reagan County experienced a similar development of irrigation wells. Eighty-one wells were drilled from 1960 to 1966. However, 55 wells that were formerly used for irrigation have either been abandoned or unused since development began. Other small areas of irrigation development are: Schleicher County, 69 wells; Midland County, 40 wells; Upton County, 39 wells (White, 1968); Ector County, 22 wells; Crockett County, 17 wells (Iglehart, 1967); Sutton County, 14 wells; Sterling County, 13 wells; and Menard County, 8 wells. The lack of soil cover and the generally rough, rocky terrain are factors that limit the use of ground water for irrigation in parts of the Edwards Plateau rather than the lack of water in the Edwards-Trinity (Plateau) aquifer.

Records of about 5,100 water wells and springs on the Edwards Plateau were tabulated during this investigation. In addition, 101 wells in Menard County and 88 wells in Crockett County were revisited in order to obtain water levels and collect water samples for chemical analysis to update the previous studies conducted in these two counties. An attempt was made to inventory all irrigation, public supply, and industrial wells and a selected number of domestic and livestock wells. Many industrial wells that were developed to supply water for drilling and development of oil and gas tests, have been abandoned or are unused after drilling ceased. Location of all inventoried wells and related data are shown on well location maps and tables of this report or in reports of other ground-water studies.

Past and Present Development

In 1950, total pumpage of ground water from the Edwards-Trinity (Plateau) aquifer on the Edwards Plateau was about 17,000 acre-feet or about 15 million gallons per day (mgd). Total pumpage for 1972 was about 86,000 acre-feet or about 77 mgd. Table 3 shows the yearly estimated ground-water pumpage from the Edwards-Tr nity (Plateau) aquifer for domestic, livestock, public supply, industrial, and irrigation uses, by county, for the period 1955.72. The following table shows the pumpage by use of ground water for 1972.

Use	1972 Pumpage (acre-feet)
Domestic	3,971.g
Livestock	6,684.I
Public supply	6.480.2
Industrial	6.762.0
Irrigation	61,910.2
Total	85,808.4

The amount of water pumped from the Edwards-Trinity (Plateau) aquifer will likely increase due to increase in population and expanded industry. The use of ground water for irrigation will remain fairly constant unless a prolonged drought should occur.

Irrigation

The calculated total amount of ground-water pumpage for irrigation from the Edwards-Trinity (Plateau) aquifer in 1972 was about 62,000 acre-feet, or about 55 mgd, and represents about 70 percent of the total pumpage during the year. Glasscock and Reagan Counties are the principal users of water for irrigation from the Edwards-Trinity (Plateau) aquifer.

Industrial

The calculated total industrial pumpage from the Edward-Trinity (Plateau) aquifer in 1972 was about 6,800 acre-feet or about 6 mgd. This amount is about 7 percent of the total water pumped from the aquifer during the year and about 800 acre-feet more than the approximately 6,000 acre-feet pumped in 1955. This increase in pumpage is due primarily to increased use of water for secondary recovery of oil (waterflood), development and growth of industrial complexes, and drilling for oil and gas. The largest amount of ground water used for secondary recovery of oil on the Edwards Plateau is in Coke, Crockett, Ector, Midland, Reagan, and Upton Counties. Ector and Reagan Counties are the principal users of ground water from the Edwards-Trinity (Plateau) aquifer for industrial purposes having used about 90,000 acre-feet and almost 24,000 acre-feet, respectively, for the 18-year period 1955-72.

Public Supply

The calculated amount of ground water pumped from the Edwards-Trinity (Plateau) aquifer for public supply decreased from about 10,000 acre-feet in 1955 to about 6,500 acre-feet in 1972. The 1972 pumpage represents about 7 percent of the total pumpage for the year. The largest amount, approximately 1,600 acre-feet, was pumped in Ector County and represents about 25 percent of all water pumped for municipal supplies from the Edwards-Trinity (Plateau) aquifer. Wells developed in the Edwards-Trinity (Plateau) aquifer supply water for towns and cities in Crockett, Edwards, Irion, Reagan, Schleicher, Sutton, and Upton Counties. This aquifer also supplements surface-water supplies for cities in Ector and Howard Counties. The town of Eden in Concho County supplements its well field, that is developed in the Edwards and associated limestones, with water from a well developed in the Hickory Sandstone. Other counties on the Plateau-Bandera, Coke, Gillespie, McCulloch, Midland, Kerr, Kimble, Kinney, Real, Sterling, Tom Green, and Uvalde-either use surface water for a municipal supply or pump water from aquifers other than the Edwards-Trinity (Plateau) aquifer. Several small communities located on the Edwards Plateau utilize privately owned, small-capacity, public-supply wells with limited distribution systems for water supply. The amount of water produced by these systems is tabulated as domestic water use.

Domestic and Livestock

In 1972, the amount of water produced from the Edwards-Trinity (Plateau) aquifer for domestic purposes on the Edwards Plateau was about 4,000 acre-feet or 3.5 mgd. This represents about 4 percent of the water pumped from the Edwards-Trinity (Plateau) aquifer during 1972. The amount of water used for domestic purposes has declined from 4,604 acre-feet in 1955 to 3,971 acre-feet in 1972. This estimate is based on the 1970 rural population and on the population of small communities without a public water supply system.

The use of water for livestock purposes pumped from the Edwards-Trinity (Plateau) aquifer in 1972 was almost 7,000 acre-feet or about 6 mgd. This represents about 7 percent of all water pumped from this aquifer during 1972. The amount of water used for livestock purposes was about 6,200 acre-feet in 1955.

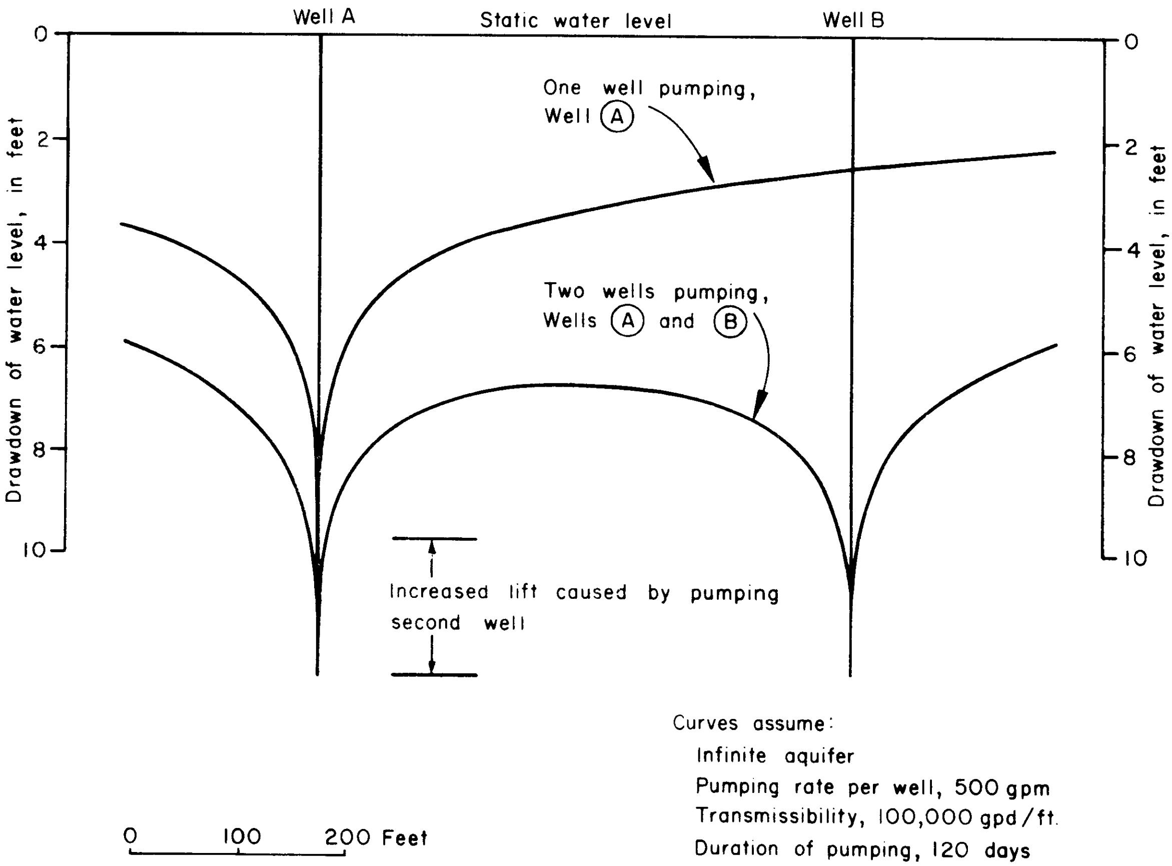
The total pumpage of ground water from the Edwards-Trinity (Plateau) aquifer for domestic and livestock purposes on the Edwards Plateau is likely to remain fairly constant or possibly decrease due to loss of rural population to the urban areas and to frequent droughts which reduce the number of animals on ranches in the region.

Future Development

Future development of the Edwards-Trinity (Plateau) aquifer is dependent upon the amount of annual precipitation, the amount of land converted to farm land, the amounts of cotton-acreage allotments, new industry, and population growth. The Upper Colorado River Authority is developing a supplementary ground-water supply from the Allurosa (Alluvium and Santa Rosa) aquifer in Ward County. The city of San Angelo has contracted with landowners in southern Tom Green and northern Schleicher Counties for a standby source to supplement their surface-water supply. They are also developing a municipal water supply from the Hickory Sandstone Member of the Riley Formation in Concho and McCulloch Counties. The potential for future development of the Edwards-Trinity (Plateau) aquifer is discussed in another part of this report.

Construction of Wells

The type of construction of water wells depends upon the intended use of the water. Wells developed for high capacity such as industrial, irrigation, or public supply are constructed by a different method than wells developed for small pumpage such as domestic and livestock use. The different methods of well construction are shown in the following diagram.



Curves assume:
- Infinite aquifer
- Pumping rate per well, 500 gpm
- Transmissibility, 100,000 gpd/ft.
- Duration of pumping, 120 days
- Specific yield, 14 percent
- Distance between wells, 500 ft.

Most of the domestic and livestock wells developed in the Antlers Formation-the basal formation of the Edwards-Trinity (Plateau) aquifer-in Ector, Midland, Glasscock, Upton, and Sterling Counties, and parts of Reagan County, have small diameter casing, generally 5 to 6 inches. The bore hole is generally cased to the bottom of the well and either torch-slotted or perforated opposite the water-bearing portion of the sandstone. Earlier wells drilled into the sand were cased only through the surficial deposits. This resulted in the loss of some wells due to caving of the sand which filled the bore hole. In the central and parts of the southern part of the Edwards Plateau, domestic and livestock wells are developed in the Edwards and associated limestones and do not require casing to prevent caving. Wells developed in the Glen Rose Formation in the southeastern part of the Edwards Plateau often have blank casing through the upper part of the limestone in order to prevent the water, which contains a high sulfate content, from entering the bore hole. Various small capacity, 1/3 to 1 horsepower, cylinder, jet, and submersible pumps are used for domestic wells. Windmills with cylinder pumps are most frequently used for livestock wells.

The two most important factors to be considered in planning domestic and livestock wells are: (1) locate the wells where contaminants from septic tanks, cesspools, privies, and barnyards will not enter the wells through surface drainage or movement of ground water; and (2) fill the annular space between the casing and bore hole with cement, and seal the casing at the top to prevent entry of vermin, insects, or other objectionable material.

The large-capacity wells, such as those used for irrigation, public supply, and industry developed in the Antlers Formation, are drilled in a manner similar to domestic and livestock wells except that the diameter of the bore hole is much larger, and a few are gravel packed. The gravel is placed in the annulus of the well from the surface casing to the bottom of the well hole. Underreaming and gravel packing the well bore below the surface casing increases the effective diameter of the well and decreases the entrance velocity of ground water when the well is pumped. During periods of heavy pumping, gravel packing will increase the specific capacity (gallons per minute per foot of drawdown) of the well, serve as a strainer to prevent entrance of fine-grained sediments into the well bore, and serve as a filling material should cavities be formed by fine-grained sediments entering the well bore when the well is being developed. Gravel packing also tends to prevent encrustation (iron cementation) of the slotted or screened section. Large-capacity wells developed in the Edwards and associated limestones are usually drilled to a large diameter, and are cased and cemented with one joint of casing, generally 10 to 30 feet. The well bore is open to the entire water-bearing section, and the well yield is sometimes increased by use of hydrochloric acid. The acid increases the permeability of the reservoir rock by enlarging the solution cavities, fractures, and joints in the vicinity of the well bore. This process, like gravel packing in a sandstone reservoir, increases the effective well diameter and the specific capacity.

Pumps used on irrigation wells are powered by electric motors or internal combustion engines fueled with gasoline, butane, natural gas, or diesel. Industrial and public supply wells are generally powered by electric motors.

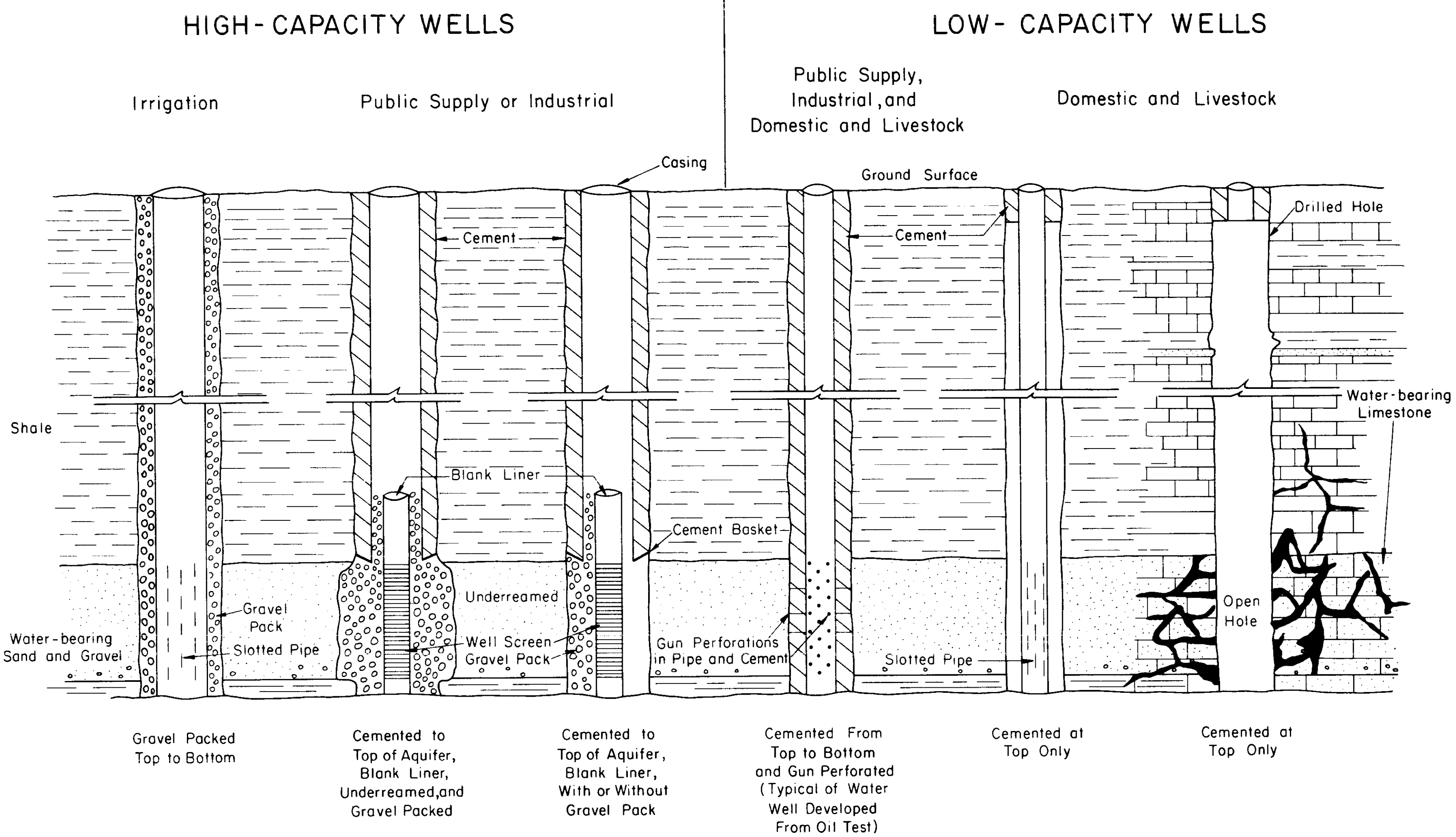
The following discussion suggests some well-completion methods that should result in increased capacity of water wells developed on the Edwards Plateau.

Large capacity wells should be spaced so that the cones of depressions do not overlap thereby causing interference and additional lowering of water levels. The following diagram shows in idealized cross section of the drawdown interference between two pumping wells and the increased lift or additional drawdown.

The size of screen openings or slots should be determined by the size and degree of sorting of the water-bearing sands and the gravel packing. Slots or screen openings that are too large will allow fine-grained sand to enter the well bore and cause “sanding up” of the well and excessive pump wear.

Larger well yields may be obtained from the Edwards and associated limestones by an artificial fracturing process. Water and sand is pumped into the well bore through tubing and into the water-bearing limestone by excessive pump pressure. This water-sand slurry creates new fractures or enlarges existing fractures, solution cavities, and joints much like acid treatment. However, the sand fills the enlarged fractures, cavities, and joints thereby creating “pipes” or conduits which permit water to enter the well bore in a steady flow. This will prevent turbulence when the well is pumped. Gravel packing will increase the specific capacity of wells developed in sandstone aquifers. The production life of a well may be lengthened by use of well screens instead of slotted or perforated casing. The size of screen openings can be made more accurate than torch slots, and the type of metal making up the screen can be selected to prevent corrosion and encrustation.

The well bore should be drilled as near vertical and straight as possible to insure that the pump will operate



Diagrams of Typical Well Construction Used to Produce Water From Sand, Gravel, and Limestone properly and will not come in contact with the casing or well bore (in uncased holes). This is especially important in wells equipped with deep well turbine pumps.

GENERAL CHEMICAL QUALITY OF GROUND WATER

The amounts of dissolved matter found by chemical analysis in ground water from the Edwards Plateau are given in Table 7 and in the referenced county reports. In Table 7, the chemical analyses are presented in milligrams per liter (mg/l) which is the preferred metric system unit. Milligrams per liter and parts per million (ppm) by weight are numerically the same if the concentration of dissolved matter is less than about 7,000 ppm and the specific gravity of the water is approximately 1.0 (Davis and Dewiest, 1966, p. 77). The following equation shows the relation between these units:

$$\text{parts per million} = \frac{\text{milligrams per liter}}{\text{specific gravity of the water}}$$

The general classification of water used in this report is from Winslow and Kister (1956, p. 5). The classification is based on the dissolved-solids concentration as follows:

Description	Dissolved-solids content (mg/l)
fresh	Less than 1,000
slightly saline	1,000 to 3,000
moderately saline	3,000 to 10,000
very saline	10,000 to 35,000
brine	greater than 35,000

Figure 16 of this report and similar figures in the various referenced county reports illustrate the general quality of ground water found on the Edwards Plateau. The following table from Doll and others (1963, p. 39-43) lists and discusses the source and significance of mineral constituents and the physical properties of natural waters.

The major portion of dissolved matter found in the ground water is from leaching of soluble substances in the soil and rocks with which the ground water comes in contact. The chemical quality of the ground water is thus affected by its environment from its point of impact on the earth as relatively pure precipitation to its final discharge from the aquifer.

Repeated leaching of the soil and rocks through which the ground water moves tends to remove excess soluble substances and thus improves the ground-water quality. This is probably an important reason why the areas of the Plateau receiving the most precipitation generally have ground water with a lower dissolved-solids content than those areas that receive less precipitation. Probable causes for the numerous exceptions to this general trend are:

(1) differences in the ease of ground-water movement that affect the quantity of leaching;

(2) differences in soil and rock composition and, possibly, the presence of original (connate) water with a high dissolved-solids content left when the rocks were deposited; and

(3) activities of man, especially the former practice of disposing of oil-field brines and other industrial wastes in unlined surface-disposal pits and from improper disposal of sewage or other organic waste material. Some contamination of ground water by organic wastes may be due to infiltration or direct entrance through improperly constructed wells. A common source of such wastes could be livestock.

Quality Standards and Suitability for Use

Industrial

The quality standards for industrial water vary depending upon the particular needs of the industrial process. Because of the wide variance in quality standards, only a general discussion can be made of water quality for industrial use.

Industrial ground water use on the Edwards Plateau can be classified into five principal categories: cooling water, boiler-feed water, process water, water for secondary recovery of oil, and water for oil and gas test hole drilling.

Cooling water is usually selected on the basis of consistency of temperature, chemical quality, and dependability of source. Waters high in calcium and magnesium salts, which cause hardness, and other scale-forming chemicals such as iron, aluminum, and silica are to be avoided since these encrust heat-exchange surfaces and thereby reduce the efficiency of the cooling process. Corrosion is another feature to be avoided in

Source and Significance of Dissolved-Mineral Constituents and Properties of Water

(From Doll and others, 1963, p. 39-43)

Constituent or property	Source or cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 mg/l. High concentrations, as much as 100 mg/l, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type water softeners.
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment. More than 1 or 2 mg/l of iron in surface waters generally indicates acid wastes from mine drainage or other sources.	On exposure to air, iron in ground water oxidizes to reddish-brown precipitate. More than about 0.3 mg/l stains laundry and utensils reddish-brown. Objectionable for food processing, textile processing, beverages, ice manufacture, brewing, and other processes. U.S. Public Health Service (1962) drinking-water standards state that iron should not exceed 0.3 mg/l. Larger quantities cause unpleasant taste and favor growth of iron bacteria.
Calcium (Ca) and magnesium (Mg)	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.
Sodium (Na) and potassium (K)	Dissolved from practically all rocks and soils. Found also in ancient brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.
Bicarbonate (HCO_3) and carbonate (CO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in mine waters and in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. Some calcium sulfate is considered beneficial in the brewing process. U.S. Public Health Service (1962) drinking-water standards recommend that the sulfate content should not exceed 250 mg/l.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in ancient brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. U.S. Public Health Service (1962) drinking-water standards recommend that the chloride content should not exceed 250 mg/l.
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils. Added to many waters by fluoridation of municipal supplies.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth, depending on the concentration of fluoride, the age of the child, amount of drinking water consumed, and susceptibility of the individual. (Maier, 1950)
Nitrate (NO_3)	Decaying organic matter, sewage, fertilizers, and nitrates in soil.	Concentration much greater than the local average may suggest pollution. U.S. Public Health Service (1962) drinking-water standards suggest a limit of 45 mg/l. Waters of high nitrate content have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding. Nitrate has been shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils. Includes some water of crystallization.	U.S. Public Health Service (1962) drinking-water standards recommend that waters containing more than 500 mg/l dissolved solids not be used if other less mineralized supplies are available. Waters containing more than 1,000 mg/l dissolved solids are unsuitable for many purposes.
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. Waters of hardness as much as 60 ppm are considered soft; 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; more than 180 mg/l, very hard.
Specific conductance (micromhos at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.
Hydrogen ion concentration (pH)	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals.

cooling water. Corrosion can be caused by acids, dissolved oxygen, carbon dioxide, sodium chloride, and magnesium chloride.

Ground water used for boilers generally must meet rigid chemical-quality standards. This is especially true for high-pressure boilers, because the high temperature and pressure cause encrustation, corrosion, and water carry-over. Iron (oxides in boiler water can cause priming and foaming. Magnesium chloride breaks down in boiler water to form hydrochloric acid. In addition, the magnesium and calcium present in most waters cause scale on the boiler tubes. Silica is an important constituent to consider in selecting a water supply for boiler feed, as it forms a particularly hard scale. The scale-forming tendency increases with an increase in boiler pressure. The recommended maximum concentration of silica for water used in boilers is as follows (Moore. 1940, p. 263):

Maximum concentration of silica (ms/l)	Boiler pressure (pounds per square inch)
40	less than 150
20	150 to 250
5	251 to 400
1	more than 400

Process water is that water incorporated into final manufactured products, such as beverages, ice, textiles, and chemicals. The water is usually subject to very rigid chemical-quality standards, some approaching the quality of distilled water. Any impurities such as high dissolved solids, that would adversely affect the quality of the product, are avoided. Water containing minimal concentrations of manganese and iron is desirable to avoid staining or discoloration.

The water produced with oil and gas, plus some supplemental water, is generally used in secondary recovery of oil. The injected water must be compatible with the oil-reservoir rock and must not contain substances which could cause plugging. Plugging can be caused by the oxidation of metallic ions, especially iron (Fe^{+++}). Suspended matter, iron bacteria, algae and fungi can also cause plugging. Sulfate-rich waters may cause a resistant deposit of barium sulfate if mixed with barium-rich waters. Alkaline water promotes iron deposits and the formation of calcium scale. Acid waters can cause corrosion of injection equipment. The water should be free of corrosive gases such as hydrogen sulfide, carbon dioxide, or oxygen.

Oil and gas test hole drilling water is subject to few, if any, quality requirements. In fact, brine is used when drilling through some of the thick salt formations found in the subsurface in some areas of the Edwards Plateau.

Irrigation

The chemical quality of irrigation water can be judged by its electrical conductivity, sodium-adsorption ratio (SAR), residual sodium carbonate (RSC), and concentration of boron. The lower the values of these characteristics, the better the chemical quality of the water. Successful use of some poor quality waters for irrigation may depend on favorable conditions of soil composition and texture, favorable climate, special irrigation practices, and adequate soil drainage. Local conditions, therefore, have much to do with the suitability of a water for irrigation.

The electrical conductivity of water is a useful and fairly accurate expression of the total concentration of soluble salts in the water. High concentrations of soluble salts in irrigation water cause the water to have a high salinity hazard. Water with a high salinity hazard may cause saline conditions to develop in irrigated soil. This limits the kinds of crops which can be grown to those which are salt tolerant, and will eventually destroy the productivity of the land unless adequate leaching and drainage remove the excess salts. Table 5 lists the relative tolerance of crop plants to salinity.

According to the U.S. Salinity Laboratory Staff (1954, p. 71):

> Waters having an electrical conductivity in the range of 750 to 2,250 micromhos per centimeter are widely used, and satisfactory crop growth is obtained under good management and favorable drainage conditions, but saline conditions will develop if leaching and drainage are inadequate. Use of waters with conductivity values above 2,250 micromhos per centimeter is the exception, and very few instances can be cited where such waters have been used successfully. Only the more salt-tolerant crops can be grown with such waters and then only when the water is used copiously and the subsoil drainage is good.

The sodium-adsorption ratio (SAR) is defined by the expression:

Table 5.—Relative Tolerance of Crop Plants to Salinity

(From Hem, 1962)

In each column the plants first named under each class are most sensitive and the last named under that class the most tolerant.

Forage Crops

Sensitive	Moderately tolerant	Tolerant
Burnet	Sickle milkvetch	Birdsfoot trefoil
Ladino clover	Sour clover	Barley (hay)
Red Clover	Cicer milkvetch	Western wheatgrass
Alsike clover	Tall meadow oatgrass	Canada wildrye
Meadow foxtail	Smooth brome	Rescue grass
White Dutch clover	Big trefoil	Rhodes grass
	Reed canary	Bermuda grass
	Meadow fescue	Nuttall alkaligrass
	Blue gramma	Saltgrass
	Orchardgrass	Alkali sacaton
	Oats (hay)	
	Wheat (hay)	
	Rye (hay)	
	Tall fescue	
	Alfalfa	
	Hubam clover	
	Sudan grass	
	Dallis grass	
	Strawberry clover	
	Mountain brome	
	Perennial ryegrass	
	Yellow sweet clover	
	White sweet clover	

Field Crops

Sensitive	Moderately tolerant	Tolerant
Field beans	Castorbeans	Cotton
	Sunflower	Rape
	Flax	Sugar beet
	Corn	Barley (grain)
	Sorghum (grain)	
	Rice	
	Oats (grain)	
	Wheat (grain)	
	Rye (grain)	

Fruit Crops

Sensitive	Moderately tolerant	Tolerant
Avocado	Cantaloupe	Date palm
Lemon	Grape	
Strawberry	Olive	
Peach	Fig	
Apricot	Pomegranate	
Almond		
Plum		
Prune		
Grapefruit		
Orange		
Apple		
Pear		

Vegetable Crops

Sensitive	Moderately tolerant	Tolerant
Green beans	Cucumber	Spinach
Celery	Squash	Asparagus
Radish	Peas	Kale
	Onion	Beets
	Carrot	
	Potatoes	
	Sweet corn	
	Lettuce	
	Cauliflower	
	Bell pepper	
	Cabbage	
	Broccoli	
	Tomato	

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

where NA^{+}, Ca^{++}, and Mg^{++} represent the concentrations in milliequivalents per liter (me/l) of the respective ions.

According to Hem (1962, p. 148-149):

> When a soil containing exchangeable Ca^{++} and Mg^{++} ions is irrigated with water in which Na^{+} greatly outnumbers other . . . positively charged ions, the calcium and magnesium of the soil will tend to be replaced with sodium.

Continued irrigation with such water will cause an alkali soil with poor tilth and low permeability.

The salinity hazard, as measured by electrical conductivity, and the sodium or alkali hazard, as measured by the SAR, were used by the U.S. Salinity Laboratory Staff (1954, p. 69-82) to prepare a classification system for judging the quality of water used for irrigation. A diagram for that classification system is presented in Figure 17. The figure also shows quality of water samples from selected wells.

The residual sodium carbonate (RSC) is another factor used in judging the quality of irrigation water. Excessive sodium carbonate concentrations cause soils to break down and lose their permeability, restricting the movement of air and water. Alkali soils will develop and the soil will lose its ability to support plant life.

Wilcox (1955, p. 11) gives the following limits for RSC for irrigation waters: water with more than 2.6 milliequivalents per liter (me/l) is not suitable for irrigation, 1.25 to 2.6 me/l is marginal, and water containing less than 1.25 me/l is probably safe.

Boron is necessary for good plant growth, however, excessive boron content will render water unsuitable for irrigation. Wilcox (1955, p. 11) stated that concentrations of boron as high as 1.0 mg/l are permissible for irrigation of sensitive crops, as high as 2.0 mg/l for semitolerant crops, and as much as 3.0 mg/l for tolerant crops. Examples of sensitive crops are deciduous fruit and nut trees and navy beans; semitolerant crops include small grains, cotton, potatoes, and some other vegetables; and tolerant crops are alfalfa and most root vegetables.

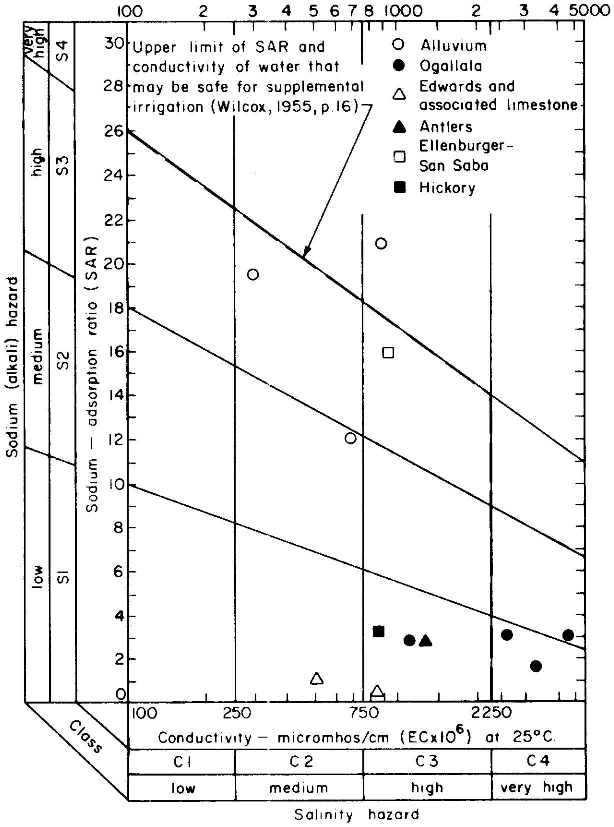


Figure 17.—Diagram for the Classification of Irrigation Waters, Showing Quality of Representative Water Samples (Adapted From United States Salinity Laboratory Staff, 1954, p. 80)

Livestock

The following table, published in 1950 by the Department of Agriculture of the State of Western Australia, shows the upper limits of dissolved-solids concentrations in water to be consumed by livestock.

Type of livestock	Upper limit of dissolved-solids concentration (mg/l)
Poultry	2,860
Pigs	4,290
Horses	6,435
Cattle (dairy)	7,150
Cattle (beef)	10,000
Sheep (adult)	12,900

The limits listed above may be useful as a general guide in some cases, but generally, water of better quality than that recommended in the table is available in all parts of the Edwards Plateau.

Because of the danger of death by nitrate (NO_3) poisoning, livestock should not be allowed to drink water containing more than 220 mg/l nitrate (Burden, 1961). Several livestock deaths have occurred recently from high nitrate ground waters in Runnels County. Also, according to Schmitz (1961), the consumption of water with a high nitrate content may be a cause of natural abortions in livestock.

Domestic

Water supplies for domestic use should be free of undesirable taste and odor and should have no color or sediment. Harmful micro-organisms should not be present.

The water analyses presented in this report describe only the dissolved-mineral matter in the water and not the sanitary condition. Water that is shown to be chemically suitable for domestic use is, therefore, not necessarily safe bacteriologically nor otherwise desirable for domestic use. Most poor water characteristics can be corrected by the proper treatment. A high dissolved-mineral content, however, is difficult and expensive to correct.

The U.S. Public Health Service has established standards for drinking water to be used on common carriers engaged in interstate commerce. The standards are intended to protect the traveling public from poisonous, unpalatable, unsightly, or digestive intolerable water. They are used in this report as a guide in judging the chemical quality of water intended for use as drinking water. According to the standards, the chemical constituents should not be present in a water supply in excess of the listed concentrations, except where more suitable supplies are not available or cannot be made available at a reasonable cost.

The following is a partial list of chemical standards adopted by the U.S. Public Health Service (1962, p. 7 and 8).

Substance	Concentration (mg/l)
Chloride (Cl)	250
Fluoride (F)	(*)
Iron (Fe)	.3
Manganese (Mn)	.05
Nitrate (NO_3)	45
Sulfate (SO_4)	250
Dissolved solids	500

*When fluoride is naturally present in drinking water, the concentration should not average more than the appropriate upper limit in the following table.

County	Annual average maximum air temperature (°F)	Recommended control limits in mg/l		
		Lower	Optimum	Upper
Bandera	81	0.6	0.7	0.8
Crockett	81	.6	.7	.8
Ector	77	.7	.8	1.0
Edwards	81	.6	.7	.8
Gillespie	79	.7	.8	1.0
Kerr	79	.7	.8	1.0
Kimble	80	.6	.7	.8
Kinney	83	.6	.7	.8
Menard	79	.7	.8	1.0
Midland	77	.7	.8	1.0
Real	81	.6	.7	.8
Uvalde	83	.6	.7	.8

These values were derived from the small number of temperature reporting stations in the area for which values of the annual mean of the daily maximum temperature are given in "Climatography of the United States," No. 86-36, published by the National Weather Service in 1965. Because of the sparsity of data points, the variation of 'temperature with latitude and elevation, and other factors, the value of the annual mean of the daily maximum temperature for an entire county should be used with caution, and it should be recognized that on the Edwards Plateau differences of several degrees in the annual mean may exist in a fairly short horizontal distance.

CHEMICAL QUALITY OF GROUND WATER IN AQUIFERS ON THE EDWARDS PLATEAU

Edwards and Associated Limestones

Although the Edwards and associated limestones and the Antlers Formation are considered a single aquifer from a regional standpoint, they are discussed separately in this section since many wells on the Edwards Plateau produce water from only the Edwards and associated lirnestones or the Antlers Formation.

The chemical quality of ground water from the Edwards and associated limestones is generally better than that in ths other aquifers on the Plateau, and the water is fairly uniform in quality. Water from the Edwards and associated limestones is characteristically very hard, and is typically a calcium bicarbonate type with sulfate and chloride occurring in relatively small quantities, each generally much less than 50 mg/l. The water contains about 200 to 400 mg/l dissolved solids. In some places, however, such as western lrion and in some isolated places in Reagan and Schleicher Counties, the concentration of dissolved solids is greater than 1,000 mg/l. Some wells in Val Verde and Kinney County produce water with 1,000 mg/l or more of dissolved solids. These wells are generally located south of U.S. Highway 90. Restricted circulation of the ground water because of the depth of the aquifer is probably a cause for the poor water quality.

The concentration of calcium is usually 50 to 100 mg/l with an average of about 75 mg/l. Most magnesium concentrations are from 10 to 50 mg/l. The average concentration is a bout 30 mg/l except in the southeastern counties where the average is about 20 mg/l. Sodium is generally less than 20 mg/l and averages 10 to 15 mg/l except in the northwestern counties where it may average 25 to 30 mg/l. The concentration of bicarbonate averages about 250 mg/l. Fluoride concentrations are generally lower in the southern and southeastern counties, where most of the water contains less than 0.5 mg/l. The water in the northwestern counties averages about 1.0 mg/l but is highly variable. Iron and manganese are not a problem in water from the Edwards and associated limestones.

The nitrate concentration is usually less than 10 mg/l. However, isolated cases of concentrations greater than 45 mg/l have been found in Bandera, Concho, Edwards, Gillespie, Kimble, Menard, Schleicher, Sutton, and Uvalde Counties. Several wells in Gillespie County yield water with a higlh concentration of nitrate. Most of these wells are near livestock pens or domestic sewerage disposal facilities and may have been contaminated by organic substances from these sources.

The water from the Edwards and associated limestones has a very low sodium hazard, and the percent sodium is usually much less than 30. The salinity hazard is usually medium and occasionally is high.

The few boron (analyses which have been made on water from the Edwards and associated limestones are presented in the following table. These analyses indicate that boron is not a problem in water from this aquifer.

County	Well	Boron (mg/l)
Edwards	JJ-55-63-301	0.4
Irion	PK-43-59-104	.2
	PK-43-59-103	.3
Reagan	UZ-44-52-502	.6
Schleicher	WY-55-12-101	.3

In summary, most of the water from the Edwards and associated limestones, with the exception of being very hard, is of excellent quality. However, excess nitrate which indicates possible contamination of the water by organic substances is found in isolated places. The water is generally suitable for irrigation except that it has a medium and occasionally a high salinity hazard.

Antlers

Most of the wells which produce water exclusively from the Antlers Formation are located in Upton, Ector, Midland, Glasscock, Howard, northern Reagan, Sterling, Coke, Tom Green, and lrion Counties. Other wells, most of which are located in Midland, Reagan, Upton, Ector, Glasscock, Crockett, Irion, Sterling, Tom Green, and Schleicher Counties, produce water from the Antlers in conjunction with water from other aquifers. The chemical quality of water from these wells is, therefore, a blend of the waters from the different aquifers.

The chemical quality of the water in the Antlers is generally poorer in the western and central parts than in the northeastern and eastern parts of the aquifer. A few wells located near the edge of the Edwards Plateau have exceptionally good quality water compared with other wells in the same general area. Local differences in ease of recharge and in movement of the ground water are probably responsible for these differences in water quality. The quality of the water in the southern part of the aquifer is not well known because few wells tap the aquifer in that area. A few wells produce water from the Antlers and from the overlying limestone in southwestern Schleicher County and in eastern Crockett County. The water from these wells generally contains more than 1,000 mg/l dissolved solids. This is more than that of water from the Edwards and associated limestones, and indicates that the water in the southern part of the Antlers Formation may be highly mineralized. Three wells in western Sutton County which produce at least part of their water from the Glen Rose Formation, or possibly from the Paluxy Sand, contain water with more than 1,000 mg/l dissolved solids and a noticeable odor of hydrogen sulfide gas. This also indicates that the water in the southern part of the Antlers may be of poor quality. Two samples of water which may be from the Antlers in western Menard County and three samples near the city of Menard indicate the aquifer may have water with from 500 to more than 1,000 mg/l dissolved solids in those areas. Two areas of lower Cretaceous sands in northern Gillespie County, identified by Barnes (1952 and 1956) as the Hensell Sand Member, are located north of the pinch-out of the Glen Rose Formation. These areas are treated as Antlers Formation in this report. The water in the Antlers in these areas is very hard and contains from 400 to about 1,000 mg/l dissolved solids. The nitrate concentration is generally less than 7 mg/l; however, water from well KK-57-34-502 in Gillespie County contained 155 mg/l nitrate. This well is near livestock pens and a residence and may have been contaminated by organic matter from these sources.

Water from the Antlers is of the calcium bicarbonate sulfate type. The water is typically very hard, and the amounts of each of the dissolved substances varies greatly from place to place. The dissolved solids average about 530 mg/l, but water with more than 1,000 mg/l is common in Upton, Ector, southwestern Glasscock, and northern Reagan Counties. The silica content averages about 20 mg/l, calcium about 110 mg/l, magnesium about 35 mg/l, sodium plus potassium about 60 mg/l, bicarbonate about 250 mg/l, and chloride about 70 mg/l. The sulfate content is commonlv highest in Upton, Midland, southwestern Glasscock, and northern Reagan Counties, where many samples contained more than 300 mg/l. Many water samples from wells in Ector County have a sulfate content of between 50 to 300 mg/l. Water from the Antlers in Howard and northeastern Glasscock Counties commonly contains about 50 mg/l sulfate. The sulfate content of water in Sterling, Coke, Tom Green, and Irion Counties is commonly less than 20 mg/l. Water samples from a few wells in Menard County, which may produce water from the Antlers, indicate sulfate concentrations of more than 500 mg/l in the western part of the county and less than 50 mg/l in the central part. Most of the water samples from the Antlers in Gillespie County contained less than 50 mg/l sulfate.

The fluoride content of the water is commonly greater than 1.0 mg/l and the average concentration is near 1.6 mg/l. A large number of water samples from the Antlers contained more than the recommended maximum for fluoride on the Edwards Plateau. The nitrate concentrations average about 14 mg/l, and only a few wells produce water with nitrate exceeding the recommended limit of 45 mg/l for drinking water. Almost all the analyses of Antlers water indicate more than 180 mg/l hardness. The water is, therefore, classified as very hard, and softening of the water is desirable for many uses.

Water from the Antlers is used for irrigation in several areas on the Edwards Plateau. The sodium hazard of Antlers water is low, and the percent sodium is characteristically less than 30. A significant characteristic of most Antlers water is that it commonly has a medium or high salinity hazard. Continued use of water with a high salinity hazard may eventually cause high salinity conditions to develop in the soils of the heavily irrigated areas of the Edwards Plateau. A high soil salinity would allow the growing of saline-tolerant crops only.

Only a few boron analyses of Antlers water are available and are listed in the following table:

County	Well	Boron mg/l)
Ector	JH-45-05-628	0.2
	JH-45-05-629	.2
	JH-45-06-804	.6
	JH-45-06-806	.6
	JH-45-06-906	.3
Glasscock	KL-44-06-501	.13
	KL-44 13-903	.16
	KL-44 20-503	.71
Midland	TJ-45-06-908	.2
Sterling	XP-44-16-402	.0l
	XP-44-15-601	.23
	XP-44-15-603	.02
	XP-44-15-604	.10

According to Scofield (1936) irrigation waters with concentrations of boron less than 0.67 mg/l are classified as good for use on boron sensitive crops. According to this classification, boron does not appear to be a problem in water from the Antlers Formation.

The development of a closed system of ground-water circulation, which has occurred in some areas of heavy ground-water pumpage, could eventually degrade the quality of ground water due to repeated reuse of infiltrated irrigation water which has dissolved salts from the soil and deposited them in the aquifer. However, data are not sufficient to indicate if such degrading has occurred in any of the aquifers on the Edwards Plateau.

In summary, the best quality water from the Antlers Formatron is found in the northeastern part of the aquifer and in some isolated places near the edge of the Plateau. Water with more than 1,000 mg/l dissolved solids is common in the western part of the aquifer, and the few water samples from the southern part of the aquifer indicate possibly high mineralization in that area. A few wells in the Antlers yield water of fair to good quality in Menard and Gillespie Counties. The water is used in many places on the Edwards Plateau for domestic purposes and is generally of fair quality. In some areas, especially in the western parts of the aquifer, the dissolved solids content is excessive. The fluoride content of the water is commonly near or above the upper limit recommended for drinking water, and the water is characteristically very hard. The medium to high salinity hazard of the water may eventually cause saline conditions to develop in the soils, and possibly in the aquifer, in certain heavily irrigated areas. This could be caused by the development of a closed circulation system of the ground water in which the salinity of the water is increased by reusing the irrigation water.

Alluvium

The chemical quality of water in the alluvium in Glasscock, Howard, Reagan, Sterling, and Upton Counties averages more than 1,500 mg/l dissolved solids. Water from wells developed in the alluvium in Concho, Irion, Kerr, Kimble, Menard, Real, Sutton, Tom Green, Uvalde, and Val Verde Counties contains less than 400 mg/l dissolved solids. The variation in chemical quality is due in part to the movement of ground water, source of recharge, and the presence of effluent in streams. In the north and west parts of the Plateau, the alluvium deposits are in hydraulic continuity with the Antlers Formation which yields water that generally exceeds the recommended limits suggested by the U.S. Public Health Service for dissolved solids, sulfate, fluoride, and chloride. Ground-water discharge (base flow) and underflow in the central and southern parts of the Plateau is from the Edwards and associated limestones into the alluvium. This water is classified as a calcium bicarbonate type, and all chemical constituents are below the recommended limits for drinking-water standards.

Fluoride is a problem in water in the alluvium on the Edwards Plateau. In the north and west parts of the Plateau, fluoride concentrations range from 0.4 mg/l in water from the alluvium in Irion County to 4.6 mg/l in Glasscock County, with a general average of 1.5 mg/l, which is above the recommended maximum. In Kerr, Kimble, Menard, Real, Sutton, Uvalde, and Val Verde Counties, the fluoride content is below the lower recommended limit of 0.6 mg/l. Water from the alluvium which contains the optimum fluoride content is found only in Concho, Howard, Irion, Sterling, and Tom Green Counties.

All water from the alluvium is classified as very hard. The hardness ranges from a low of 219 mg/l in Irion County to a high of 1,710 mg/l in Upton County. The average hardness of water is 831 mg/l in the northwestern part of the Plateau and 324 mg/l in the southern part.

The following table shows a comparison of the averages of several chemical constituents in water from the alluvium in the northwestern and southern parts of the Plateau.

Substance	Average concentration in northwestern part (mg/l)	Average concentration in southern part (mg/l)
Calcium (Ca)	247	87
Magnesium (Mg)	59	24
Sodium (Na)	157	31
Sultate (SO)	628	36
Chloride (Cl)	238	32
Fluoride (F)	2.1	.45

The cities of Junction, Leaky, Menard, and Sterling City obtain water from the alluvium for public supplies. Except for excessive hardness, the water generally meets the suggested standards for drinking-water quality. The dissolved solids concentration is 550 mg/l in water used by Sterling City, 430 mg/l in water used by Menard, 324 mg/l in water used by Leaky, and 226 mg/l in water used by Junction.

Water from the alluvium has been used for irrigation successfully for several years. Data from the chemical analysis of water samples collected show that the salinity hazard (based on the specific conductance) is medium in water from alluvial wells in Menard, Midland, Irion, Real, and Uvalde Counties; high in water from wells in Sterling County; and medium to high in water from wells in Tom Green County. Water having a high to very high salinity hazard should be applied to well-drained soils, and the crops should be salt tolerant.

Lower Cretaceous

Large areas of the Edwards Plateau are without any direct evidence of the quality of the ground water in the lower Cretaceous formations. However, the available evidence indicates that the water in these formations is probably highly mineralized. The major causes for this apparently wide-spread high mineralization are the slow movement of ground water into the lower Cretaceous formations, which causes a slow rate of removal of dissolved salts from the aquifer, and the solution of anhydrite and gypsum beds that are present in some places in the upper member of the Glen Rose Formation.

A relatively impermeable zone at the base of the Edwards and associated limestones restricts movement of water into the underlying Glen Rose Formation and lower Cretaceous sandstones. The presence of this zone is demonstrated by the many springs which flow from the base of the Edwards and associated limestones. These springs are especially common along the southeastern side of the Plateau where the base of the Edwards and associated limestones is exposed.

Gypsum and anhydrite beds in the upper member of the Glen Rose are the probable cause of a high sulfate content in water from this formation in Uvalde, Edwards, Real, Kerr, and Kendall Counties. According to Alexander and Patman (1969, p. 12), the Glen Rose in Kimble County contains some gypsum and anhydrite and yields slightly saline water to only one well in the county. They recommend that wells drilled through the Glen Rose and completed in the lower Cretaceous sandstones be cased to prevent the entrance of water from the Glen Rose. The total extent of the gypsum and anhydrite beds in the Glen Rose is not known. However, water frorn the Trinity Group is high in sulfate in many places on the Edwards Plateau, and if these beds are encountered when drilling a well, they should be cased and cemented in order to prevent the contamination of better quality water.

Very few wells on the Edwards Plateau produce water exclusively from the Glen Rose or the lower Cretaceous sandstones. A few wells in Crockett, Sutton, and Val Verde Counties produce at least in part from these formations, and a few wells are found along the eastern edge of the Plateau. There are, however, a large number of wells located just off the eastern edge of the Plateau which produce from these formations.

Well HJ-!54-27-303, located in western Crockett County, produces water from the lower Cretaceous sandstones. The water from this well contains 1,259 mg/l dissolved solids, 444 mg/l sulfate, 226 mg/l chloride, and is very hard. Well HJ-54-35-803, also located in western Crockett County, probably produces water from the lower Cretaceous sandstones. The water from this well contains 1,505 mg/l dissolved solids, 343 mg/l sulfate, 474 mg/l chloride, and is classified as very hard. These wells are located near the edge of the Plateau where the aquifer is probably subject to better circulation of ground water than in the central areas of the Plateau. The water quality in the lower Cretaceous sandstones may, therefore, be better at these locations than in the central areas of the Plateau.

A number of wells in southern Crockett, northern Val Verde, and western Sutton Counties are known to produce at least part of their water from the Paluxy Sand. The sulfate content of water from these wells ranges from 27 to 710 mg/l and the dissolved-solids content ranges from 360 to 2,154 mg/l. Comparing the quality of water produced by wells developed in the Edwards and associated limestones with the water quality from the lower Cretaceous aquifer, it appears that water from the lower Cretaceous is high in sulfates and dissolved solids in the western part of the Edwards Plateau.

Most of the other wells which produce from the lower Cretaceous aquifer are located on or near the outcrop of the Glen Rose along the edge of the Edwards Plateau in Edwards, Uvalde, Real, Bandera, Kerr, Gillespie, Kimble, and Menard Counties.

According to Long (1962, p. I), the Glen Rose Formation yields small quantities of rather highly mineralized water to wells in Edwards County. He also stated that springs in the Glen Rose discharge water that is generally less mineralized than that obtained from wells, and that nearly all the wells and springs producing water from the Glen Rose are in the southeastern part of the county, where the Edwards and associated limestones have been removed by erosion or are very thin.

There is no information available on the quality of the ground water in the lower Cretaceous sandstones in Kinney County, and there are no wells in the county which are known to draw water from the Glen Rose (Bennett and Sayre, 1962).

Welder and Reeves (1962, p. 2) reported that the Glen Rose in Uvalde County yields saline water at many locations in the county, and that the principal objectionable constituent is high concentrations of calcium and magnesium sulfate. They also stated that in most places in the county, except in that part on the Edwards Plateau, the water from the Glen Rose is probably too saline for most uses, and that the lower Cretaceous sandstones will likely yield only saline water.

Long (1958, p. 13) reported that little is known regarding the quality of the water in the lower Cretaceous sandstones in Real County. However, he states that eight samples of water from the Glen Rose in Real County contains from 304 to 3,550 mg/l dissolved solids. The samples with the highest dissolved-solids content also contained a high sulfate content which probably was due to the solution of gypsum in the Glen Rose. The water in these eight samples was very hard, ranging from 307 to 2,680 mg/l.

Reeves and Lee (1962, p. 21 and 22) stated that most of the wells in Bandera County yield mixed waters from several formations; therefore, it is difficult to draw reliable conclusions regarding the character of the water supplied by different aquifers for the county as a whole.

The analyses frorn 4 wells that draw from the Hosston and Sligo Formations... in the southeastern part of the county showed a range in dissolved solids from 464 to 561 mg/l and a range in hardness frorn 166 to 261 mg/l. Available data are too meager to permit a general statement regarding the quality of the water in the Hosston and Sligo throughout the county. However, the few samples taken indicate that the water, though hard, is suitable for most purposes. Most wells that draw from the Pearsall Formation in Bandera County are cased only to the top of the massive limestone beds of the lower member of the Glen Rose Formation; consequently, most of the wells produce a mixture of waters from both formations. Analyses of samples from 4 wells... which produce from the Pearsall Formation only, show dissolved-solids contents ranging from 549 to 1,400 mg/l. Sulfate appears to be the most objectionable constituent, ranging from 14.6 to 810 mg/l.

Water samples were collected from 6 wells that draw from only the lower member of the Glen Rose. The dissolved-solids content ranged from 310 to 601 mg/l and the sulfate content ranged from 16 to 198 mg/l. The most objectionable characteristic of the water is its hardness; all the water samples would be classed as very hard.

The water from the upper member of the Glen Rose varies widely in quality. Many of the wells yield saline water which is particularly high in sulfate content. The dissolved-solids content ranged from 10 to 2,910 mg/l. All the water was very hard. The water of poor quality seems to be associated with the evaporite beds. The anhydrite dissolves fairly readily in the percolating ground water, thus contributing large amounts of sulfate to the water. Where the evaporite beds lie at shallow depth, particularly in the vicinity of streams, they may be highly leached, and the contained water may be of relatively good quality.

On the Edwards Plateau in Bandera County, the quality of the ground water in the Trinity Group is probably greatly influenced by the amount of recharge the formations receive. A relatively impermeable zone at the base of the Edwards and associated limestones, probably allows only small amounts of water to move down through the Edwards and associated limestones into the lower formations. It is probable, therefore, that any good quality water to be found in the Trinity Group on the Edwards Plateau in Bandera County is limited to the edges of the Plateau and in the areas near major streams; in short, wherever recharge is made easier by the absence of an impermeable zone above the aquifers.

One well (RJ-56-52-301) located on the Edwards Plateau in Kerr County produces water from the Hensell Sand Member of the Pearsall Formation. The water is very hard, containing 1,080 mg/l hardness. The water also contains 876 mg/l sulfate and 5.6 mg/l iron, making it undesirable for many uses. The well is located about 9 miles from the nearest outcrop of the Glen Rose Formation, therefore recharge to the Trinity Group in the area of the well must all come from the overlying Edwards and associated limestones. The quality of the water from this well probably is representative of the poor quality water to be found in the Glen Rose Formation and the lower Cretaceous sandstones in the interior areas of the Plateau. In the Glen Rose and lower Cretaceous sandstones located off the edge of the Edwards Plateau, Reeves (1969, p. 10, 19, and 20) found that the water is generally of good quality except that iron and fluoride are commonly excessive, and the water in the upper member of the Glen Rose Formation is usually slightly saline.

Only a few wells are known to produce water from the Trinity Group on the Edwards Plateau in Gillespie County, and no information is available on the chemical quality of the water from these wells. In the areas of Gillespie County which are not on the Edwards Plateau, there are many wells which produce from the Trinity Group. According to Mount (1963, p. 18), the water from the Hensell Sand Member of the Pearsall Formation in the area near the city of Fredericksburg is, with some exceptions, of good chemical quality and satisfactory for public supply. Concentrations of individual constituents and dissolved solids show a large degree of variation from place to place. Chemical analyses show that most of the water is high in bicarbonate and iron. In some instances the nitrate and chloride concentrations are objectionably high. The dissolved-solids concentration of water samples from 20 wells that penetrate the Hensell ... ranges from 531 to 1,371 mg/l. A well in the south part of Fredericksburg is reported to have produced water containing 7,052 mg/l dissolved solids.

In describing the chemical quality of the water in the lower Cretaceous in Kimble County, Alexander and Patman (1969, p. 28) reported that the fresh water from the Hensell Sand Member of the Pearsall Formation is suitable for most uses, but some of the slightly saline water was unsuitable for domestic, livestock, or irrigation uses. All of the samples from the 27 wells supplied from the Hensell ... contained very hard water; in 14 samples, the fluoride content ranged from 0.9 to 4.0 mg/l in 7 samples, the chloride content ranged from 260 to 432 mg/l; and in 16 samples the iron content ranged from 0.37 to 7.6 mg/l. Field determinations of the iron content of water from an additional 69 wells ranged from 0.1 to 5.0 mg/l, and 47 samples exceeded 0.3 mg/l.

Alexander and Patman (1969) also mapped the areas in which the Hensell contains slightly saline water and the areas in which almost all the water is fresh. In general, the line separating these two types of water is parallel to the eroded edge of the contact between the Edwards and associated limestones and the Trinity Group. The slightly saline water is found toward the interior cf the Edwards Plateau, and the fresh water is found in the areas on or near the outcrop of the Trinity Group. Greater recharge is evidently the cause of the fresher water in the Trinity Group in its outcrop area than where it is covered by the Edwards and associated limestones.

Baker, Dale, and Baum (1965, p. 19) reported that the Trinity Group yields water to several wells in the outcrop area along the San Saba River valley and in the southeastern part of Menard County. The chemical quality of the water from the Trinity ranges over wide limits. The dissolved-solids content ranged from about 800 to about 2,700 mg/l. In most of the wells in the Trinity, the chloride content was less than 250 mg/l. In general, the water from the Trinity Group is of poorer quality than that in the Edwards and associated limestones; consequently, wells are completed in the Edwards and associated limestones, where possible.

In summary, slow recharge and the presence of gypsum and anhydrite in places probably cause the waters in the Glen Rose Formation and the lower Cretaceous sandstones to be highly mineralized in most areas of the Edwards Plateau.

Only a few wells on the Edwards Plateau tap these formations. However, many wells off the edge of the Plateau, especially on the east side, obtain slightly saline to fresh water from the formations.

Hickory

The Hickory Sandstone Member of the Riley Formation of Cambrian Age contains fresh to slightly saline water from the outcrop area east of the Edwards Plateau to a depth of about 1,800 feet below sea level on the Plateau. The water is a sodium bicarbonate type and, although generally hard, is suitable for most uses. Hardness ranges from a low of 34 mg/l in water from a municipal well (DZ-42-50-101) at Eden in Concho County to 334 mg/l in water from a test well (SS-42-60-502) in McCulloch County.

Iron content in water from the Hickory Member ranges from 0.12 in water from a municipal well at Brady to 4.03 mg/l in a test well in southeastern Concho County. The high iron content in the water appears to occur in the upper part of the Hickory. A water sample collected from a test well (DZ-52-49-301) in southeast Concho County, in which the entire Hickory section was open hole, contains 4.03 mg/l iron. In the second test well (SS-42-60-502) in McCulloch County, about 4 miles east of the test well in Concho County, the upper part of the Hickory was cased off. A water sample collected from this test well contains 0.28 mg/l iron.

The chloride content of water from the Hickory is usually well below the maximum recommended with the exception of water from the municipal well at Eden which contains 350 mg/l chloride. Sulfate like chloride is low. The highest sulfate content is 111 mg/l in the test well (SS-42-60-502) in McCulloch County.

Most of the water from the Hickory is suitable for irrigation. The water has a low sodium hazard and a medium to high salinity hazard. The downdip limit, or the depth at which water may become unsuitable for irrigation use in the Hickory, is about 1,500 feet below sea level. However, local variation in water quality and type of soil to be irrigated may alter individual conditions.

Ellenburger-San Saba

Water contained in the Ellenburger-San Saba aquifer along the eastern edge of the Edwards Plateau is hard but otherwise of good chemical quality. The water is a calcium bicarbonate type which is characteristic of water contained in a limestone-dolomite reservoir. The dissolved solids range from 313 mg/l in water from well TH-56-04-603 in Menard County (Baker, 1965, p. 84) to 1,010 mg/l in water from well C-3 in northern McCulloch County (Mason, 1961, p. 82). Iron content is generally below the maximum concentration of 0.3 mg/l recommended by the U.S. Public Health Service.

The town of Fredericksburg in Gillespie County obtains most of its water supply from two wells developed in the Ellenburger Group. The dissolved solids in water from these wells is 683 and 717 mg/l, which is slightly higher than the maximum recommended for drinking water. The concentrations of other chemical constituents are: bicarbonate, 365 and 437 mg/l; chloride, 74 an3 178 mg/l; sulfate, 35 and 66 mg/l; sodium, 46 and 98 mg/l; magnesium, 37 and 51 mg/l; and calcium, 77 and 105 mg/l.

The town of Melvin in western McCulloch County obtains water from a well (SS-42-52-401) developed in both the Ellenburger-San Saba and Hickory aquifers. The water from this well is extremely hard (253 mg/l), and the iron content is 0.68 mg/l, which is more than double the recommended maximum. The water is a sodium bicarbonate type and, except for the hardness and iron content, is of good quality considering the distance the well is located from the surface outcrop of the reservoir rocks.

Water from wells developed in the Ellenburger-San Saba aquifer in east Menard, northeast Kimble, and southeast Gillespie Counties is generally acceptable for irrigation purposes. The sodium hazard is medium in water from wells in Menard County and high in Kimble and Gillespie Counties. The water from wells in northern McCulloch Courty is marginal to unsuitable for irrigation use unless applied to soils with good drainage and salt-tolerant plants. The sodium hazard range is from 14 to 21, and the salinity hazard is high with specific conductivities above 750 micromhos per centimeter.

Ogallala

Water from the Ogallala in Glasscock and Midland Counties is typically a sulfate chloride type, whereas in Ector County it is a sulfate bicarbonate type.

The quality range is from fresh to moderately saline with dissolved solids ranging from 296 to 6,500 mg/l. The average for dissolved solids in water from the Ogallala in Glasscock, Midland, and Ector Counties is about 2,000 mg/l.

The fluoride content in the water ranges from 0.4 to 7.4 mg/l, with an overall average of 2.8 mg/l. This average content is considerably greater than the recommended upper limit of 1.0 mg/l.

Sulfate in water from the Ogallala creates problems when used for domestic purposes. Sulfate combines with magnesium or sodium and causes a definite laxative effect on persons not used to ingesting water containing magnesium sulfate or sodium sulfate.

The salinity hazard is high to very high in water from the Ogallala. Normally, this water would be unsuitable for irrigation use over a prolonged period; however, due to the sandy soil in this area and growing of relatively salt-tolerant crops, no wide-spread harmful effects have been noted.

Permian

Characteristically, water from Permian rocks is high in sulfate, calcium, and chloride, and is very hard (Table 7 and Figure 16).

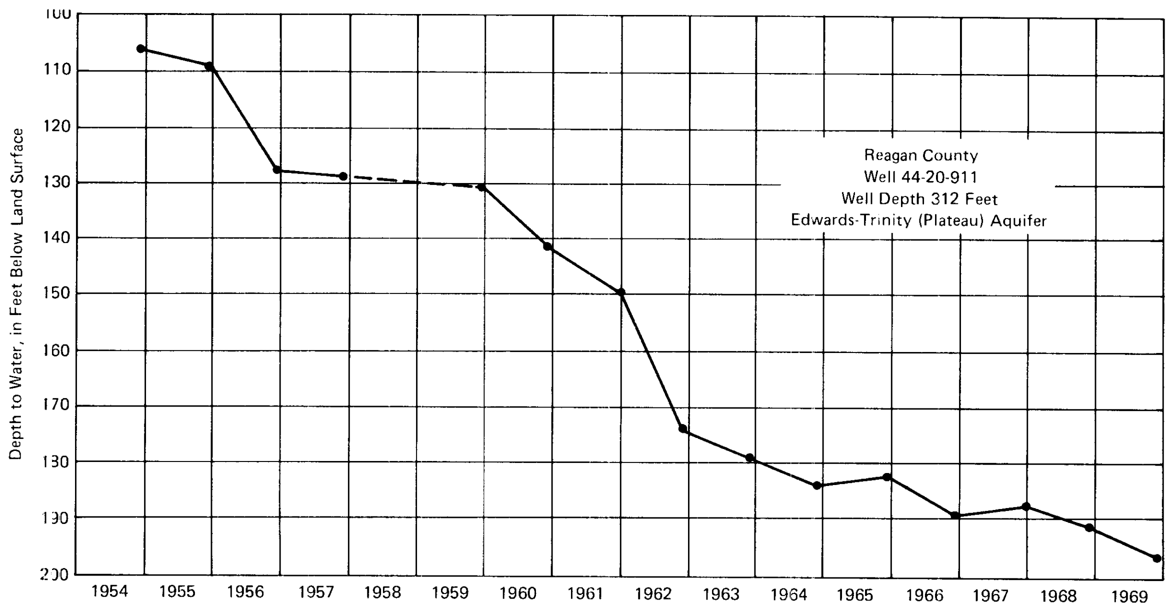
Of the 16 wells sampled during this study, 15 yielded water containing more than 250 mg/l of sulfate. The dissolved solids ranged from 367 to 47,100 mg/l, and hardness ranged from 314 to 8,050 mg/l.

Wells developed in the Permian in the common corners of Schleicher, Sutton, Menard, and Kimble Counties yield good quality water which is low in dissolved solids. This is due to recharge from the overlying Cretaceous limestones. One well (WY-55-15-601) in Schleicher County yields a calcium bicarbonate type water with a dissolved solids content of 364 mg/l.

GROUND-WATER PROBLEMS

Decline of Water Levels and Yield of Wells

Declining water levels and decreasing well yields in the Edwards-Trinity (Plateau) aquifer are becoming a problem to water users in the northwestern part of the Edwards Plateau. As shown on Figure 18, the greatest recorded decline is in well KL-44-20-846 in southern Glasscock County, where the water level has declined 114 feet from 1937 to 1966. This is an average decline of 3.9 feet per year. According to Figure 19, which



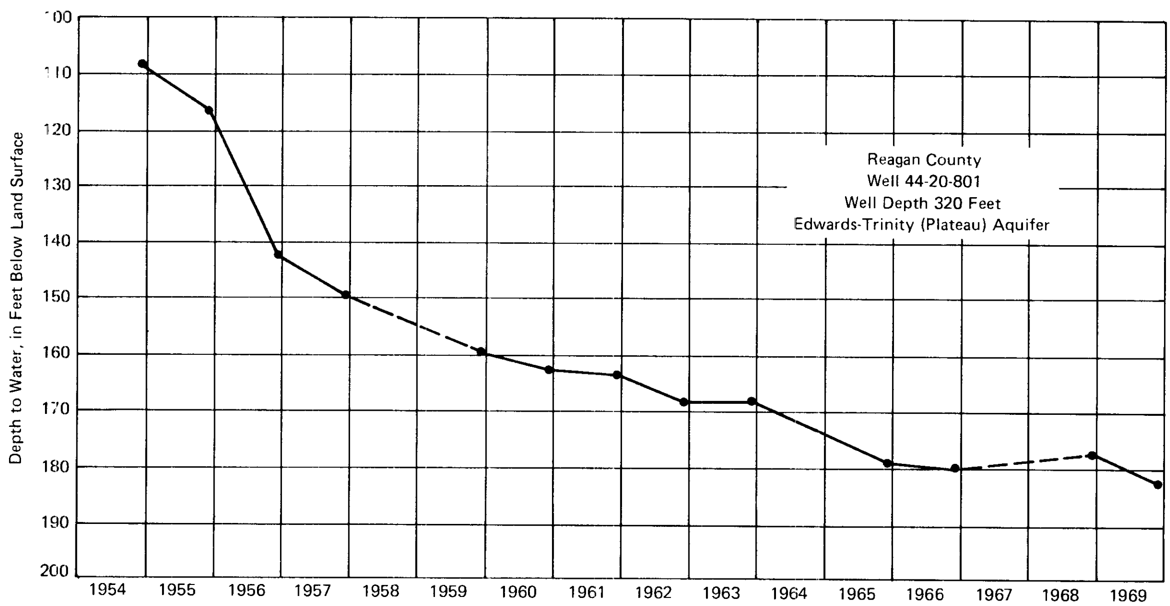


Figure 19.—Hydrographs of Water Levels in Selected Wells

shows hydrographs of selected wells, the water level in well UZ-44-20-911 in northern Reagan County has decline 95 feet in 18 years.

Water levels in public supply wells in Ector County have declined from 15 feet to 67 feet in 21 years. The decline of water levels in the county would likely have been much greater had it not been for the development of a surface water public supply and a saline-water supply for secondary recovery of oil.

Water levels have declined as much as 80 feet in an industrial well field in northeast Sterling County. This well field was developed in 1955 to furnish fresh water for secondary recovery of oil.

Water levels in Schleicher, Upton, and Midland Counties have declined from a few feet to over 50 feet. The water level in well WY-55-03-201 in Schleicher County, declined 51 feet from 1957 to 1970. Decline of water levels in Upton County ranged from 2 feet to 34 feet (White, 1968, p. 32).

Water levels in a small area of southeastern Midland County are presently declining about one foot per year.

The southern and southeastern parts of the Edwards Plateau has experienced little decline of water levels in the Edwards-Trinity (Plateau) aquifer due to a lack of heavy withdrawals by irrigation or industrial water use.

Well yields have declined in the heavily pumped areas due to lowered water levels and plugging or encrustation of the screened or slotted sections opposite the water-bearing zone. A decline in the coefficient of transmissibility due tc lowering of water levels and probable encrustation of the screened section has occurred in well UZ-44-36-304 in Reagan County. On January 30, 1959 (well completed November 1958), the coefficient of transmissibility was 3,000 gpd/ft, and on May 5, 1966, the coefficient of transmissibility was 2,155 gpd/ft; a decline of 845 gpd/ft.

Production of Oil-Field Brines and Method of Disposal

The disposal of brines into unlined surface pits is a potential hazard to the fresh-water aquifers on the Edwards Plateau. This brine seeps into the ground much like precipitation on the land surface. Surface disposal pits in the region are generally constructed by explosives, drilling, and bulldozing the surface and near-surface Cretaceous limestones. This method of excavating tends to enlsrge the existing fractures in the limestone or create new fractures which facilitates the seepage or downward percolation of brines into the subsurface and thence into the aquifer. Although the lake surface evaporation rate is high (see Table 1), the evaporation rate of brine in surface pits is considerably less than that of fresh water due to oil or oil scum on the brine surface. Even if all the water placed in a surface-disposal pit was evaporated, the accumulation of salts in the pit would remain as a threat to surface drainageways, the land surface, and fresh ground-water aquifers.

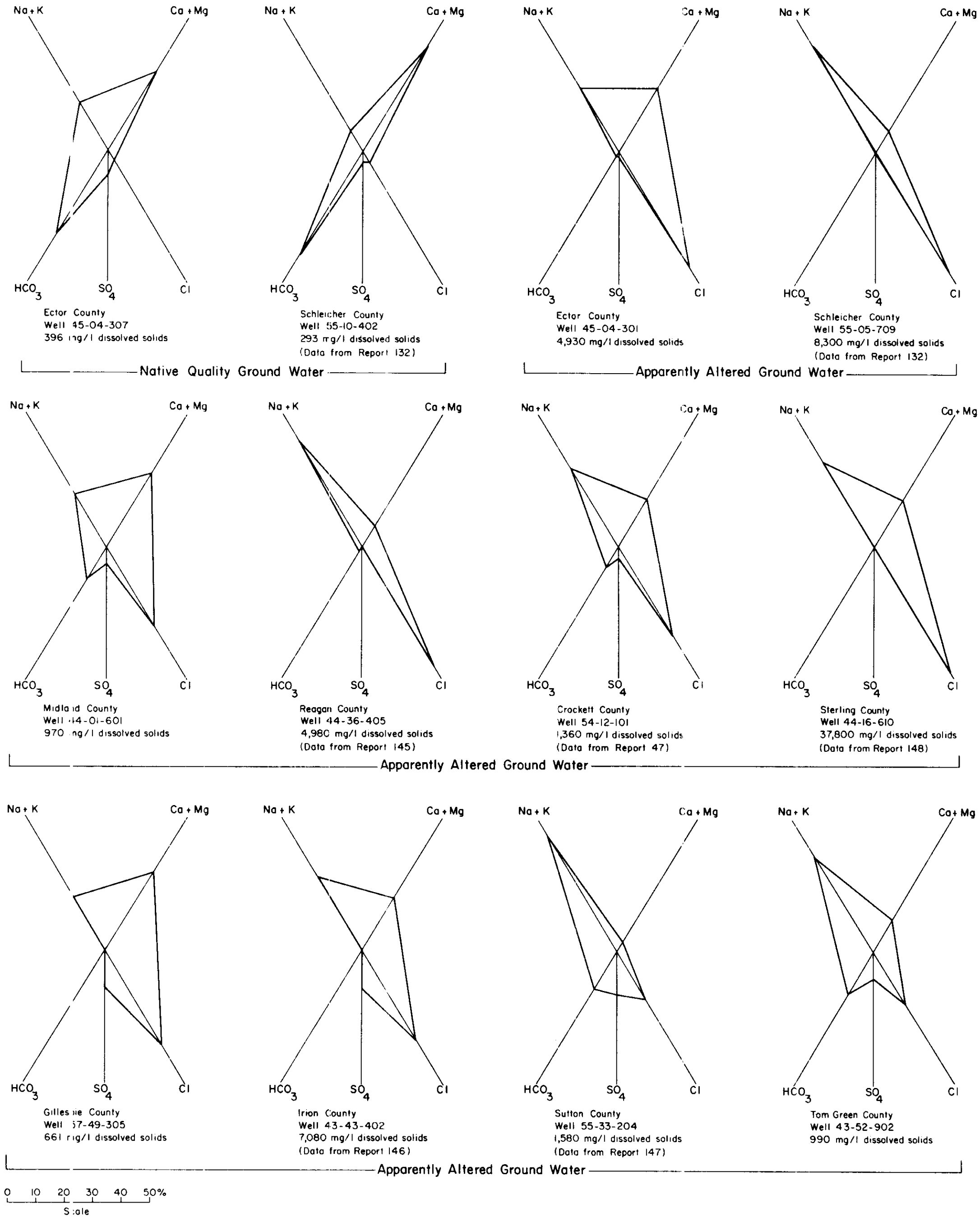
Figure 20 shows the reported amounts of oil-field brine produced and the methods of disposal by oil and gas fields in the Edwards Plateau study area for the years 1961 and 1967. The total brine production for the area was 140,977,728 barrels (18,171 acre-feet) in 1961 and 213,932,399 barrels (27,574 acre-feet) in 1967. In 1961, a total of 36,151,638 barrels (4,659 acre-feet), or about 26 percent of the total brine produced, was reportedly placed into surface pits; 104,715,609 barrels (13,497 acre-feet) was reportedly injected into the subsurface by injection wells; and 110,481 barrels (14 acre-feet) was disposed by miscellaneous methods such as dumping into surface drainageways and on county roads. In 1967, a total of 13,442,987 barrels (1,732 acre-feet) or about 6 percent of the total was reported placed into surface-disposal pits; 200,446,658 barrels (25,836 acre-feet) was reported injected into the subsurface by injection wells; and 42,754 barrels (5.5 acre-feet) was disposed by miscellaneous methods described above.

The statewide “no-pit” order of the Railroad Commission of Texas which became effective on January 1, 1969, has considerably reduced the amount of brine being disposed into surface pits. However, the large amount of brine previously disposed by this method not only affects the present chemical quality of ground water but likely will continue to affect the quality for a long period of time at the present rate of ground-water withdrawal.

The natural water contained in the Edwards-Trinity (Plateau) aquifer is characterized by a low chloride to sulfate ratio. Generally a one-to-one chloride to sulfate ratio is typical for water from the Edwards and associated limestones compared to a ratio that ranges from one-to-three to one-to-five in water from the Antlers (Trinity) aquifer. However, selected quality diagrams (Figure 21) of water samples collected from wells in several counties on the Edwards Plateau show the water to contain a chloride to sulfate ratio of almost 40:1 in well UZ-44-36-405. Water from wells in Reagan County shows a wide variation in quality as shown by chemical analysis of water samples from two wells about 4 miles north of the Big Lake oil field in west central Reagan County. Water from well UZ-44-43-804 contains 890 mg/l dissolved solids, 261 mg/l chloride, and 2:l chloride to sulfate ratio. Water from well UZ-44-43-805, about 200 feet southeast of well UZ-44-43-804, contains 10,100 mg/l dissolved solids, 5,840 mg/l chloride, and a 16:1 chloride to sulfate ratio. A probable cause of the high chloride content in the ground water from some wells in the area is the past practice of disposing brines into a playa lake about 1 mile north of the Big Lake oil field.

Improperly or inadequately cased oil or gas wells are a potential hazard of ground-water supplies in the Edwards Plateau region. The Oil and Gas Division of the Railroad Commission of Texas has been designated as the agency responsible for seeing that oil and gas wells are properly constructed, and the Texas Water Development Board provides information to oil operators and the Railroad Commission concerning the depth to which usable-quality water should be protected during drilling for and production of oil or gas.

The Railroad Commission rules require that aquifers containing usable quality ground water be



Distance along each axis shows concentration of the ion (in milliequivalents per liter) expressed as a percentage of the total concentration of dissolved solids

Figure 21

Diagrams of Chemical Analyses of Native Quality Ground Water and Apparently Altered Ground Water in Selected Wells

protected by surface casing that has been set and cemented, or by alternate protection devices. The depth of protection varies from area to area due to varying depths of ground-water aquifers. Some older oil fields were developed before field rules pertaining to surface-casing requirements were adopted. Some examples are the first wells drilled in the Big Lake field of Reagan County, the McCamey field in Upton County, and the Howard-Glasscock field in Howard County. Due to the lack of surface-casing requirements for these earlier wells, they have been inadequately cased, have little or no cement around the casing, or in some instances, have had the casing removed from the bore hole.

AVAILABILITY OF GROUND WATER

Edwards and Associated Limestones Aquifer

In the southern part of the Edwards Plateau, the Antlers Formation thins, becomes shaly, and disappears. Within this area, water is present in the Edwards and associated limestones and in the alluvium which is hydrologically interconnected with the Edwards and associated limestones along the Frio, Nueces, Sabinal, and Guadalupe River. Because the water is contained primarily in solution cavities, caverns, and fractures of the Edwards and associated limestones, estimation of the quantity of water available is extremely difficult. Therefore, water availability is calculated on the basis of perennial yield. This involves estimation of natural discharge (base-flow and spring-flow) and artificial discharge (pumpage). The total natural and artificial discharge within all or parts of the Concho, San Saba, Llano, Devils, Nueces, Frio, and Guadalupe River basins on the Edwards Plateau is about 625,000 acre-feet annually. However, only about 300,000 acre-feet of the water is available on a perennial basis if a system of wells was developed to intercept this amount of water. An attempt to pump as much as 300,000 acre-feet per year of ground water may not be practical or desirable. Because of the large area and the relatively low water-yielding ability of the aquifer, a large number of wells would have to be developed. Also, ground-water development of this magnitude would cause a significant reduction in the base flow of the major streams and many of the spring-fed tributaries.

Antlers Aquifer

The sands of the Antlers Formation occur in the northwestern part of the Edwards Plateau. The highest coefficient of transmissibility was 10,000 gpd/ft in northwest Midland County and the lowest was 1,100 gpd/ft in Upton County. The coefficient of storage ranged from 0.0387 in east central Sterling County to 0.148 in southeast Miclland County (Table 4).

About 71 million acre-feet of water is in transient storage in the Antlers Formation on the Edwards Plateau. This estimate is based on the volume of saturated thickness of the sandstone and a specific yield of 0.074. Included in the total volume of the Antlers is the saturated thickness of the Santa Rosa Formation of Triassic Age in those areas where the two formations are in hydraulic continuity (Figures 11 and 12).

The following table shows the estimated water in storage in the Antlers Formation:

County	Water in storage (acre-feet)
Coke	722,198
Crockett	15,338,738
Ector	1,533,399
Glasscock	4,638,209
Howard	284,173
Irion	10,227,428
Kimble	147,361
Menard	52,803
Midland	1,872,685
Reagan	14,398,913
Schlercher	5,590,841
Sterling	2,868,446
Sutton	5,847,677
Tom Green	1,644,248
Upton	6,328,581
Total	71,495,700

The transmission capacity of an aquifer (the ability of a part of the aquifer to transmit water under given hydraulic gradients) is another method for estimating the amount of ground water available. It is known that the amount of water that will move through a segment of an aquifer is dependent upon the coefficient of transmissibility, the hydraulic gradient, and the length of the aquifer segment perpendicular to the flow. These factors can be expressed by the equation

$$Q = TIW,$$

in which Q is the quantity of water in gallons per day; T is the coefficient of transmissibility; I is the gradient (slope) in feet per mile; and W is the width of flow cross section in feet.

With the present water-level gradient of 20 feet per mile, an overall coefficient of transmissibility of 2,720 gpd/ft, and a flow cross section of 125 miles, an estimated 7,600 acre-feet of water is available on a perennial basis from the Antlers in the western part of the Edwards Plateau. This amount includes the water contained in the alluvium which is hydrologically interconnected with the Antlers along the North and Middle Concho Rivers.

Lower Cretaceous Aquifer

The lower cretaceous water-bearing rocks are composed of the Glen Rose Formation, Hensell Sand Member of the Pearsall Formation, and the Hosston and Sligo Formations.

Well development in the Glen Rose is limited to the southern part of the Edwards Plateau and generally in areas where the Edwards and associated limestones are not present or do not contain an adequate water supply.

The amount of discharge from the Glen Rose as base flow to streams in the southern part of the Plateau cannot be accurately determined from streamflow records. However, assuming that 10 percent of the base flow of streams in the southern part of the Plateau is from the Glen Rose, then 20,000 to 30,000 acre-feet is estimated to be discharged annually from the formation.

The Hensell Sand Member of the Pearsall Formation is known to produce water to wells in Bandera, Edwards, Gillespie, Kerr, Kimble, Real, and Uvalde Counties in the southeastern part of the Edwards Plateau. Many of the wells developed in the Hensell are capable of producing only a few gallons of water per minute. The largest reported yields, about 200 gpm, are from wells located in Gillespie County. An aquifer test conducted on a well completed in the Hensell in the Fredericksburg area of Gillespie County (Mount, 1963), indicates the coefficient of transmissibility was about 600 gpd/ft and the coefficient of storage about 0.00007. The data collected during this study are inadequate to determine the availability of water from the Hensell; however, Mount and others (I 967, p. 71) stated that the annual yield from the Hensell was perhaps less than 50,000 acre-feet.

The Hosston and Sligo Formations compose the basal rocks of the Cretaceous System in the southern part of the Edwards Plateau. Several wells have been developed in these formations in Kerr, Bandera, and Uvalde Counties along the edge of the Plateau. These formations may be water-bearing on the Plateau; however, because ground water is available in the overlying rocks of the Edwards-Trinity Plateau aquifer, few if any water wells penetrate the Hosston and Sligo. Five aquifer tests were conducted by the U.S. Geological Survey on public-supply wells owned by the city of Kerrville (Reeves, 1969). These tests indicated that the coefficient of transmissibility ranged from 15,000 to 24,000 gpd per foot and averaged about 20,000 gpd per foot. The coeffficient of storage ranged from 0.00002 to 0.00005. Results of these tests are not necessarily applicable to other areas on or near the Edwards Plateau due to changes in porosity, permeability, and saturated thickness of the aquifer.

Hickory Aquifer

The Hickory Sandstone Member of the Riley Formation is an important aquifer in Mason and McCulloch Counties. Fresh to slightly saline water is produced by a few wells developed in the Hickory in Gillespie and Concho Counties. However, based on results of aquifer tests, well development, and water quality, less water is available from the Hickory in these counties than in Mason and McCulloch Counties.

Results of several aquifer tests are listed in the following table:

County	Coefficient of transmissibility (gpd/ft)	Coefficient of storage	Specific capacity (gpm/ft)
Gillespie	6,500	0.00004	6.30
Do.	4,000	-	6.20
Mason	14,500		
Do.	43,000	-	8.65
McCulloch	19,000	0.0001	—
Do.	20,000	0.00009	—
Do.	29,000	-	
Do.	38,000	0.0001	

The amount of water available from storage in the Hickory is difficult to estimate due to lack of data. Mason (1960, p. 27) estimated that one million acre-feet of ground water was available from storage in McCulloch County. This amount of ground water is based on (1) a storage coefficient of 0.0001 and an assumed specific yield of 0.1 for the part of the Hickory under water-table conditions; and (2) an assumed storage coefficient of 0.0001 and water levels lowered to a depth of 500 feet below land surface in the artesian part of the aquifer.

Mount and others (1967, p. 79) stated that at least 50,000 acre-feet of ground water was available on a perennial basis from the Hickory aquifer. However, this amount appears to be very conservative in view of the areal extent, thickness of the aquifer, and recharge to the aquifer bot' from precipitation and the flow of the San Saba, Llano, and Colorado Rivers across the Hickory outcrops.

Ellenburger-San Saba Aquifer

The Ellenburger Group and the San Saba Limestone Member of the Wilberns Formation contain fresh to slightly saline water along the eastern edge of the Edwards Plateau in Gillespie, Mason, and McCulloch Counties. This aquifer is a potential source of water in parts of Concho, Kimble, and Menard Counties. The coefficient of transmissibility range from 75,000 to 100,000 gpd/ft as determined by aquifer tests conducted on public-supply wells in Gillespie County (Mount, 1963). Mount and cthers (1967, p. 75) estimated that 20,000 or more acre-feet of ground water is available for development on an annual basis from the Ellenburger-San Saba aquifer.

AREAS FAVORABLE FOR FUTURE DEVELOPMENT

The areas most favorable for further development of wells that yield 50 gpm or more are located in the central and southern part of the region. Based on known well yields and approximate saturated thickness of the Edwards-Trinity (Plateau) aquifer, areas favorable for development are: western Schleicher County, northern Sutton County, central and southwestern Edwards County, southern Val Verde County, northeastern Menard County, east central Crockett County, and southern Reagan County.

Areas in Crockett, Irion, Reagan, and Sterling Counties, where the Santa Rosa Formation is in hydrologic contact with the Antlers Formation, are potentially favorable for development of additional ground water. Testing and development of these potential sources of ground water had not been conducted when the field work was done; however, the Santa Rosa produces water in nearby Mitchell County and at Sterling City in Sterling County.

The area least favorable for development is in the northwestern part of the Plateau where the saturated thickness of the Antlers is thin and the water levels are declining (Figure 18).

CONCLUSIONS

Five aquifers underlie the Edwards Plateau region. These are, in order of importance and development, the Edwards-Trinity (Plateau), the alluvium, the lower Cretaceous, the Hickory, and the Ellenburger-San Saba. The Ogallala is adjacent to the northern limit of the Plateau and is an important aquifer locally.

Approximately 308,000 acre-feet of ground water is estimated to be available on a perennial basis from the Edwards-Trinity (Plateau) and the alluvium aquifers. About 40,000 acre-feet is available from the Cow Creek, Hensell, and Glen Rose of the lower Cretaceous, with an additional undetermined amount from the Hosston and Sligo. The amount of ground water available from the Hickory aquifer is not known. Except for public-supply use, only a small amount of well development is expected in the Hickory because of the depth to the aquifer. The amount of ground water available from the Ellenburger-San Saba is not known. The downdip extent of the aquifer containing fresh to saline water is less than that of the Hickory because of a more rapid increase in dissolved minerals with depth in the ground-water in the Ellenburger-San Saba aquifer. It is estimated that 2,015,OOO acre-feet of ground water is available from the Ogallala aquifer in Ector, Glasscock, and Midland Counties.

The quantity of ground water pumped during 1972 from aquifers on the Edwards Plateau is estimated to be 86,000 acre-feet or 77 million gallons per day. Of the total quantity of water pumped, about 62,000 acre-feet was used for irrigation and about 6,800 acre-feet was used for industrial purposes.

In the northwestern part of the Plateau, more ground water is being pumped from the Antlers Formation than is being recharged. In the southern part of the Plateau, about 300,000 acre-feet of water is available for development from the Edwards and associated limestones. Areas of the central part of the Plateau which are relatively flat and stream valleys with deeper soils are best suited for irrigation. Development of large-capacity wells in these areas for irrigation of grains and grasses would be of great benefit to increased livestock production, especially in the event of a prolonged drought.

An expanded program of water-level and water-quality monitoring is needed in the northwestern part of the Edwards Plateau where the water levels are declining in the Antlers Formation, and the water is marginal in quality.

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CONCHO COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
DZ-42-41-502	Progress Petroleum Co. of Texas	Speck Ranch No. 4
810	Mullins-Davis & Davenport	E. L. Martin No. 1
909	Eltex Ltd.	Do.
910	do	E. L. Martin No. 3
42-712	B. A. Duffy	Burley Burk No. 1
43-706	E. M. Thomasson	C. T. Keys No. 1
903	Walter C. Nelson	Jim Rice No. 1
49-906	Morgan Drilling Co.	Anton Lubke No. 1
50-125	Northern Ordnance, Inc.	Henry Community No. 1
126	do	Leta Sorrell
127	do	Lee Community
706	Signal Oil Corp.	Sam Waring No. 1
805	Murray Petroleum	Luster Lockett No. 1
806	Schimmel Production Corp.	Sam Waring No. 2
51-302	Cosden Petroleum Corp.	G. W. Jenkins No. 1
402	Mae Belcher	Will Loveless No. 1
603	James L. Duffy & Watchern Oil & Gas Co.	Mrs. Lula Noyes No. 2
52-106	Lamb & Ford Drilling Co.	Jim Rice No. 1
57-105	Southern Minerals Corp.	A. R. Henderson No. 1
106	B. A. Duffy	Robert Wilson No. 1
107	El Producto Oil Co.	Do.
207	Dobbs & Bradshaw	J. W. Welty No. 1
305	Nash-Cook Oil Co.	Georgia Wooten, et al. No. 1
58-104	Mintex Oil Co.	Elizabeth Waring Ranch No. 2
60-101	Anzac Oil Corp.	G. R. White No. 1
43-56-402	Progress Petroleum Co. of Texas	Cora A. Henderson No. 1

CROCKETT COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
HJ-54-04-805	Haynes & V. J. Drilling Co.	Shannon Estate No. 1
13-804	Ralph Pembrook	University Lands No. 1-12

Tabulation of other oil and gas tests used for subsurface control is in Texas Water Development Board Report 47.

ECTOR COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
JH-27-58-604	Texas Company	Texaco Incorporated No. 1-B
59-404	Sinclair Oil & Gas Co.	R. B. Cowden No. 3
405	Coronet Oil Co.	Cummins No. 13
501	Phillips Petroleum Co.	Nobles No. 2
502	do	Embar No. 40
803	Pan American Petroleum Corp.	W. F. Cowden No. 15-C-Deep
804	do	Scharbauer No. 14-P-Deep
915	do	Scharbauer No. 18-M
916	Lario Oil & Gas Co.	Blakeney No. 3-F
60-410	Pan American Petroleum Corp.	W. F. Cowden No. 1-A
501	do	North Cowden Unit Block 13 No. 17
502	do	O. B. Holt No. 9-E
601	do	N. C. Cowden Unit Block 15 No. 5
803	Mid-Continent Petroleum Corp.	Blakeney No. 7-A
920	Pan American Petroleum Corp.	J. M. Cowden No. 27
61-601	do	David Fasken No. 1-AV (Inc.)
704	Ralph Pembrook	Fasken No. 1
904	Herman Brown	Ratliff No. 1
62-504	Pan American Petroleum Corp.	Fasken No. 1-AX
707	Lone Star Producing Co.	Mrs. E. J. Neathery No. 1
708	Blackwood-Nichols	Neathery No. 1-5
810	Sinclair Oil & Gas Co.	David Fasken No. 1
45-03-101	Cities Service Oil Co.	Slator No. 8
102	do	Slator No. 1-F
203	Humble Oil & Refining Co.	W. F. Cowden No. 1
303	Pan American Petroleum Corp.	Scharbauer No. 14-I-Deep

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
JH-45-03-504	Mac Donald Oil Corp.	M. B. Cochran No. 1
602	Gulf Oil Corp.	C. A. Goldsmith No. 489-56
603	do	C. A. Goldsmith, et al. No. 517-56
702	Sunray Mid-Continent Oil Co.	Texaco Incorporated No. 2-A
804	Texaco Incorporated	J. E. Parker No. 1-E
902	Atlantic Richfield	Texaco Incorporated No. 4-N
04-203	Forest Oil Corp.	Texaco Incorporated No. 1-L
606	Cities Service Petroleum Co.	J. L. Johnson San Andres Unit Tr. 7 No. 3
704	Gulf Oil Corp.	Goldsmith No. 743-56
904	M. W. J. Producing Co.	Cowden No. 1
05-114	Sinclair Oil & Gas Co.	L. E. Wight No. 1
212	Humble Oil & Refining Co.	Augusta Barrow No. 1-B
213	do	Augusta Barrow No. 9
403	Cities Service Petroleum Co.	Johnson Unit Tr. 13 No. 14
704	do	Johnson San Andres Unit Tr. 29 No. 3
931	Continental Oil Co.	Johnson No. 11-B
06-104	Texaco Incorporated	S. W. Ratliff No. 1
11-203	Forest Oil Corp.	Pure-Parker No. 1
12-105	Pan American Petroleum Corp.	J. E. Parker No. 1-C
202	Chambers & Kennedy	J. E. Parker No. 1
601	do	Cowden No. 1-A
801	Texaco Incorporated	Ector No. 9-F-Fee
802	Atlantic Richfield	LPG Storage No. 1
13-109	Milestone Drilling Co.	Cowden No. 1-A
406	Pan American Petroleum Corp.	E. F. Cowden No. 1-D
605	E. E. Reigle, et al.	Maurice No. 2-C

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
JH-45-13-704	Amerada Petroleum Co.	Texaco Incorporated No. 1-F
806	Cities Service Oil Co.	Foster No. 6-B
14-207	Forest Oil Corp. & Cities Production Co.	Fee 41 No. 2
508	Ada Oil Co.	W. Cowden No. 1
707	Cities Service Oil Co.	Foster No. 1-J
803	Bright & Schiff	E. W. Cowden No. 1
21-105	Cities Service Oil Co.	Edwards No. 1-C
203	do	Foster No. 4-N
306	Kelly Bell	Foster Unit No. 1
22-303	Texaco Incorporated	Ector No. 2-AG-Fee

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
JJ-55-44-703	J. S. Cullinan, II, et al.	Holman No. 8-B
45-901	Humble Oil & Refining Co.	W. L. Miers No. 1
46-701	Sinclair Oil & Gas Co.	Do.
801	Humble Oil & Refining Co.	W. L. Miers No. 1-B
51-302	Winters Oil Co., C. A. Young, & H. J. Hodge, Sr.	Paul Turney No. 1
901	Spencer Chemical Co.	Fred T. Earwood No. 1
52-401	H. H. Side	Paul Turney No. 1
501	P. M. Shannon	Ed Jackson
901	Great Expectations Oil Corp.	Ed C. Mayfield No. 2
53-403	V. J. Meyer	Billy Holland No. 2
55-201	Dan Auld	H. L. & Charlie Peterson No. 1
502	Ray Pool Drilling Co.	Peterson
701	Texas Co.	Mrs. H. H. Hough
56-301	Humble Oil & Refining Co.	John H. Guthrie No. 1
901	Humphrey & Wynne	Joe Sid Peterson No. 1
903	Dan Auld	L. K. Henderson No. 1
59-501	Hank Avery	Wardlaw Bros. No. 1
60-101	Sanford & Craig	Mrs. Mira Wardlaw No. 3
201	Creslenn Oil Co.	Mrs. Mira Wardlaw No. 1
202	McBride Oil Co.	Wardlaw No. 3
61-301	Knickerbocker Operating Co.	Sarah Higgins, et al.
803	Shell Oil Co., Inc.	E. Honeycutt No. 1
63-601	Dan Auld, et al.	C. & H. Peterson
801	Amon G. Carter	F. D. Sweeten No. 1
64-302	James Dalglish, et al.	Sid Peterson
303	X. K. Stout	J. S. Peterson No. 1
56-49-601	Dan Auld	Mamie Rigsby No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
JJ-56-49-801	Dan Auld	L. F. Hankins No. 1
50-601	McMan Oil & Gas Co.	Walter Schreiner No. 1
57-201	H. M. Naylor Oil Co.	Loyd Mitchell No. 1
58-101	Lecuno Oil Corp.	Bedford Shelmire No. 1
501	Plateau Oil Co.	Mrs. S. A. Hatch
70-03-901	Albert M. Griffith	C. B. Wardlaw & X. H. Whitehead No. 1
04-902	Tucker Drilling Co., Inc.	Wardlaw Bros., et al. No. 1
05-101	Slagter Producing Co.	W. E. Whittenburg No. 1
303	Richmond Drilling Co.	Brown No. 1
15-101	Humble Oil & Refining Co.	O. D. Collins No. 1
16-101	Paul Teas	B. J. Stewart No. 1
22-102	Empire Gas & Fuel Co.	O. L. McNealy, Jr.
24-201	Gale Oil Co.	Neal Jernigan
401	Phillips Petroleum Co.	Carson No. 1-A

GILLESPIE COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
KK-56-47-501	C. C. Williams	Oliver Hopf No. 2
48-901	Thousand Island Oil Co.	Hayden Estate No. 1
57-49-106	B. L. Raborn, Jr.	Joe Burkett, Jr., et al. No. 1
50-402	do	E & G Lochte

GLASSCOCK COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
KL-28-58-902	Pan American Petroleum Corp.	S. C. Houston No. 1-A
59-403	Texas National Petroleum Co.	Edmond Tom No. 1
504	Sun Oil Co.	Grady Cross No. 1
604	Sinclair Oil & Gas Co.	G. T. Hall No. 1
703	Landrath Prod.	Houston No. 1
803	A. K. Guthrie	Spruce No. 1
804	J. Roy Derrick	Sanders No. 1-23
60-406	Mallard Petroleum Inc.	G. T. Hall No. 1
502	Penn	Edwards No. 1
503	World Oil Co.	W. P. Edwards Estate No. 1
610	Simms Oil Co.	Edwards No. 1
611	do	McDowell No. 1
703	Youngblood & Youngblood	Do.
808	Fuhrman Petroleum Corp.	L. S. McDowell No. 1
809	Merriwether, et al.	McDowell No. 2
907	Phillips Petroleum Co.	Do.
908	World Oil Co.	McDowell No. 1-8
61-109	Lion Oil Co.	Coffee No. 5-C
418	Amerada Petroleum Corp.	Coffee No. 6
419	do	R. C. Coffee No. 5
420	California Co.	Baker No. 2
523	do	Jones No. 1
803	do	E. F. Turner No. 1
62-507	Gulf Oil Corp.	H. R. Clay No. 11
609	J. M. Huber	Reed No. 1
706	California Co.	Currie No. 2
707	Standard Oil Co.	W. B. Currie No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
KL-44-02-604	Amerada Petroleum Corp.	Bertie Boone No. 1
904	do	K. S. Boone No. 17-7
03-301	Landreth	Houston No. 1
501	Pan American Petroleum Corp.	E. L. Powell No. 3
603	Mann	Powell No. 1
04-111	Sohio Petroleum Co.	Landamy No. 1
421	Champlin Oil & Refining Co.	E. L. Hillger No. 1
601	Shell Oil Co.	Currie No. 1
810	Ray Smith Drilling Co.	Calverley No. 1
05-113	R. B. Stallworth, Jr.	Barkhurst No. 1
208	Ralph Lowe	Neal-Ballinger No. 1
601	Bond Oil Co.	Schafer No. 1
06-404	Renn Oil	Do.
804	R. S. Anderson	Eva Cole No. 1
10-612	Allison Producing Co.	Judkins Walton No. 2
909	Atlantic Refining Co.	Schrak No. 24-2
11-309	Shell Oil Co.	McDaniel No. 1
509	Jake L. Hamon	Brunson No. 1
807	Golston Oil Corp.	Meadors No. 1
12-109	John Y. Francis	W. H. Clark No. 1
201	Texaco Incorporated	J. B. Calverly
208	R. R. Herrell	Marshall Cook No. 1
608	Texaco Incorporated	Currie No. 1
13-320	Sinclair Oil & Gas Co.	Henrietta Long No. 1
806	Gibson & Johnson	Mann No. 1
14-210	M. W. J. Producing Co.	Clyde Reynolds No. 1
18-306	Sinclair Oil & Gas Co.	Texaco Incorporated No. 1-B
19-306	Hanley Co.	L. C. Clark No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
KL-44-19-412	Amerada Petroleum Co.	Texaco Incorporated No. 2-I
512	Sinclair Oil & Gas Co.	Fannie Boyd No. 3
602	Murphy Corp. & Ashland Oil & Refining Co.	M. L. Couey No. 1
20-113	Sinclair Oil & Gas Co.	L. C. Clark No. 1
421	American Republic Corp.	Buckner Orphan's Home No. 1-17
553	J. J. August & Assnc. & J. Roy Derrick	Jurecek No. 1
606	Placid Oil Co.	Sanders No. 1
21-502	Standard Oil Co. of Texas	Viola Scherz No. 1
806	Union Texas Petroleum Corp.	Rape No. 46-A1
22-201	Seaboard Oil Co. of Delaware	Bishop No. 1-A
404	Humble Oil & Refining Co.	Myrtle B. Frost No. 1
710	Cities Service Oil Co.	Barbee No. 4-A

Table 8. Oil Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
PK-43-25-703	Geochemical Survey	C. Harris Test Hole No. 6
704	do	C. Harris Test Hole No. 10
705	do	C. Harris Test Hole No. 2
802	do	C. Harris Test Hole No. 9
26-906	Honolulu Oil Corp.	Wall No. 1
33 103	Geochemical Survey	C. Harris Test Hole No. 11
104	do	C. Harris Test Hole No. 7
105	do	C. Harris Test Hole No. 8
206	do	C. Harris Test Hole No. 3
706	Alvon Oil & Gas	A. A. Sugg No. l-AA
41-203	Tucker Drilling Co.	A. A. Sugg No. 1
402	Virgil Latham	J. H. Clark No. 1
604	Pan American Petroleum Corp.	A. A. Sugg No. 1
905	Amerada Petroleum Co.	I. P. Van Keuren No. 1
906	Threeway Drilling Co.	A. A. Sugg No. 2
907	do	A. A. Sugg No. 1
42.104	Monsanto Chemical Co.	Lena No. 1
202	Pan American Petroleum Corp.	A. A. Sugg No. 1-C
503	Hill & Flannery	J. M. Nutt No. 1
43-501	Standard of Texas	Bryant No. 1-B
49-304	Sinclair Oil & Gas Co.	Henry Lindley No. 1
402	do	Lorena Wilson No. 1
507	Clyde Crabb	W. M. Noelke No. 1
610	Sinclair Oil & Gas Co.	Bert Mayse No. 1
611	do	Sammie H. Suggs No. 1
612	British American Oil Producing Co.	Noelke No. 1
613	do	Noelke No. 1-S. W. D.

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
PK-43-49-614	Tom Bomar Well Service	R. A. Manning No. 1
903	Atlantic Refining Co.	Noelke No. 1
50-106	Edwards Petroleum Co.	Frank Lindley No. 1
411	L. E. Scherck & Phillips-Stringer	Leta A. Crawford No. 1
507	William Wolf	J. M. Nutt Estate No. 5
603	Curtis Inman	R. K. McMillan No. 1
702	Williams & Williams Drilling Co.	W. M. Noelke No. 1
58-311	Shell Oil Co., Inc.	Tankersley Estate No. 1
44-38-904	Kirby Petroleum Co.	Sawyer Cattle Co. No. 1
39-206	Furhman	Sugg Estate No. 1
40-203	Signal Oil & Gas Co.	Ela C. Sugg No. 1
801	do	Ela C. Sugg No. 2
47-305	Humble Oil & Refining Co.	W. A. Blakey No. 12
306	Sunray DX Oil Co.	Ela C. Sugg No. 1
702	Humble Oil & Refining Co.	W. A. Blakey No. 9
802	G. C. Bingham	Ela C. Sugg No. 1
805	do	Ela C. Sugg No. 1-C
806	Bobby M. Burns & D & D Drilling Co.	Ela C. Sugg No. 1
902	Frost & Fleming	Sinclair Becton No. 1
48-203	Russell Maguire	Ela C. Sugg No. 1-D
304	Benedum & Trees	A. A. Sugg
404	Rodman, Noel & Black	Sugg No. 1
504	Russell Maguire	Ela C. Sugg No. 1-C
505	do	Ela C. Sugg No. 1-A
705	Sinclair Oil & Gas Co.	Ela C. Sugg No. 1-33
801	Western Drilling Co.	Sugg No. 1-27
55-301	Sunray DX Oil Co.	Ela C. Sugg No. 1-A
306	McIntyre Oil Co.	Ela C. Sugg No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
PK-43-55-510	C. P. Simpson	Mrs. Elta Murphy No. 2
601	Sunray DX Oil Co.	Mrs. Elta Murphy No. 1
603	do	Mrs. Elta Murphy No. 1-A
812	Russell Maguire	Sol Mayer No. 1
813	Austral Oil Exploration Co.	Do.
56-102	Sinclair Oil & Gas Co.	J. R. Scott No. 11
303	Sunray DX Oil Co.	Becton No. 1
401	P. H. Williams	G. J. Ashe No. 1
505	Western Drilling & Murry Petroleum	Do.

Table 8.-Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
R J-56-43-80 1	Tucker Drilling Co.	M. B. Schreiner
51-502	Humble Oil & Refining Co.	W. R. Schreiner
62-301	S. W. Forester	Bailey
501	Edmunds Drilling Co.	J. W. Calvin
801	-	Mrs. H. C. Hanszen
804	British-American Oil Co.	Jasper-Moore No. 1
63-502	Edmunds Drilling Co.	W. F. Stelzer
504	do	G. Voss
607	J. R. Johnson	City of Kerrville No. 7
901	do	City of Kerrville No. 9
64-402	Edmunds Drilling Co.	D. Hainlen
403	do	City of Kerrville
701	do	City of Kerrville No. 11
68-01-103	Rowsey & Taylor Oil Co.	G. Walker
204	B. F. Lackey	C. R. Blank
406	L. Bergmann & Sons	R. 0. Perkins
69-03-201	Continental Oil Co.	G. F. Schreiner
503	Woodward & Co.	W. Auld
04-601	Phillips Petroleum Co.	C. 0. Whitworth
701	Mull Drilling Co.	A. Wilson, Jr.
06-301	E. Schmidt, et al.	H. Real
40 1	Tucker Drilling Co.	F. F. Fisher
07-902	W. E. Page	E. W. Brown, Jr.
08-101	Edmunds Drilling Co.	City of Kerrvi l le-Ai rport
704	G. L. Rowsey	Eleanor Henderson Lewis, et al.
16-20 2	Ohio Oil Co.	J. H. Saul

Table 8.-Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
R K-55-24-207	Lauderdale & Straughan, et al.	Edith Murr No. 1
402	Tucker Drilling Co., Inc.	J. D. Cowsert No. 1-A
404	Sun Oil Co., et al.	– Trimble No. 1
502	Texas Pacific Coal & Oil Co.	0. T. Murr No. 1
608	King Resources Co.	Johnson No. 1
701	Sunray DX Oil Co.	Ollie T. Murr No. 1
32-202	Aztec Oil Co.	J. S. Farmer No. 1
807	Ben J. Taylor	Grosenbacher No. 1
40-l09	Atlantic Refining Co.	John R. Bailey No. 1
110	West Texas Oil & Royalty Corp. & Sojourner Drilling Co.	Mrs. W. Faulkner No. 1
502	Skelly Oil Co.	M. P. Reick No. 1
705	Delvatex Petroleum Corp.	Paterson No. 1
801	H. F. Wilcox	Meta R. Reick No. 1
901	Seneca Development Co.	Mary B. Patterson No. 1
48-301	0. N. Beer, Inc. & Toto Gas Co.	Hill No. 1
602	J. S. Michael	Mary B. Patterson No. 1
56-17-502	G. W. Strake	J. Y. Rust, et al. No. 1
504	Thomas Drilling Co.	A. D. Rust Ranch No. 1
601	Katz Oil Co.	C. B. Nasworthy No. 1
702	Tucker Drilling Co., Inc.	A. D. Rust No. 1
804	Thomas & Ludlaw	Russell No. 1
902	Guffey Drilling Co. & R. F. Schoolfield	Rust No. 1-F
18-402	Phillips Petroleum Co.	Spiller No. 1
605	Brazos-Menard Oil Syndicate & Thomas Ledlow	Mears No.1
701	G. W. Strake	R. R. Spiller No. 1
19-401	R. H. Erwin	G. R. Kothman No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
RK-56-25-302	J. C. Ranfro & C. L. Richardson	Dan O. Morales No. 1
401	Hunt Oil Co.	Ruth Simon Bode No. 1
505	Casex	Mudge No. 4
909	do	Ethel Mary Mudge No. 2-A
26-111	Anzac Oil Corp.	H. H. Lawler No. 4
201	do	H. H. Lawler No. 1
202	Humble Oil & Refining Co.	Irma Lawler Woodward No. 1
301	Anzac Oil Corp., et al.	W. L. Pfluger, Jr., et al. No. 1
402	Auld, Scrwab, Carlisle	Weaver Baker No. 1
501	Anzac Oil Corp.	Lottie Bolt No. 3
502	Anzac Oil Corp., et al.	H. H. Lawler No. 2
701	Plateau Oil Co.	J. M. Anderson No. 1
27-313	Home Oil & Refining Co.	J. D. Fisher No. 1
705	Ben Banner	Frank Baker No. 1
801	Mudge Oil Co.	P. T. Hodges No. 1-Wilson
33-104	J. W. Hancock	E. H. Harrison No. 1
34-202	Anzac Oil Corp.	– Bolt No. 4
701	Barron Kidd	J. W. Johnson No. 1
703	Mobil Oil Co.	Burt Ranch No. 2
801	Barron Kidd	J. W. Johnson No. 5
804	Mobil Oil Co.	Burt Ranch No. 4
805	do	Burt Ranch No. 5
35-503	Enfield Services, Inc., et al.	John L. Phillips No. 1
803	Delvatex Petroleum Corp.	Beasley No. 1
37-702	Forest Development Corp.	Dillard Stapp
41-403	Cities Service Oil Co.	S. B. Nelson No. 1-B
503	Tucker Drilling Co., Inc.	Coke Stevenson No. 2

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
RK-56-41-504	Tucker Drilling Co., Inc., et al.	Coke Stevenson No. 3
601	Cecil Haden	Stevenson No. 1
46-402	O. W. Killam	A. L. Gibson No. 1

Table 8.-Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
SY-27-55-801	Pan American Petroleum Corp.	Cowden No. 2
5'6-701	Gulf Oil Corp.	G. W. Glass No. 1-E-B
901	Ashland Oil & Refining Co.	Tant Lindslay No. 1
63-20 1	Pan American Petroleum Corp.	Gladis Holt Cowden No. 1
64-101	Blackwood & Nichols	Stimson No. 1
28-49-801	Tide Water Assoc. Oil Co.	Dickenson No. 1
51-701	Pan American Petroleum Corp.	F. E. Mulkey No. 1
58-101	Union Sulphur & Oil Corp.	Snyder & Arnett No. 1
59-101	Central Drilling Co.	Central Drilling Co. No. 1

MENARD COUNTY

Table 8.-Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
TH-42-5'7-4 10	Wayne Allison	Fritz Volkmann No. 1
609	Tucker Drilling Co.	W. C. McKee No. 1
610	Honolulu Oil Corp.	B. K. Neel No. 1
710	General Crude Oil Co.	Joe Wilhelm No. I-I
810	C. C. Winn	Walter Menzies No. 1
59-808	J. C. Barnett	Callan City Co. No. 1
43-64-512	L. G. Priest	J. P. Sorrell Ranch No. 1
809	Humble Oil & Refining Co.	Mary E. Rogers No. 1
818	J. H. Rowsey & G. L. Rowsey	Do.
914	Thomas Drilling Corp.	R. S. Winslow Estate No. 1
55-08-I 17	Fryer & Hanson Drilling Co.	J. M. Treadwell No. 2
207	T. A. Kirk & H. L. Neeb	Edith Runge No. I-A
610	Furney & Polk, et al.	W. W. Russell Estate No. I-A
613	Furney & Polk	W. W. Russell Estate No. 1
16-211	B. A. Duffy	Sol Mayers No. 1
605	Deep Rock Oil Corp.	M. C. Bevans No. 1
56-01-108	Carl G. Cromwell, et al. (Reported as Duffey & Loufbourrow)	R. S. Winslow No. 1
03-604	G. A. Clements	Murchison No. 1
908	Carpenter & Robbins	Carpenter & Robbins No. 1
09-I04	C. H. Murdick	George S. Allison No. 1
10-313	A. R. Ekholm	Jacoby Brothers No. 1
507	H. F. Wilcox Oil & Gas Co.	Lee Murchison No. 1
11-113	I. A. Stephens	Seth Kothman No. 1
501	American Republic Corp.	Bennie Bradford No. 1
12-402	F. H. Carpenter	Royal No. 1
18-108	H. M. Naylor Oil Co.	C. R. Thos. W. Nasworthy No. 1

MIDLAND COUNTY

Table 8.–Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
TJ-27-63-401	Albert Plummer	Mary King No. 1
402	Kern Co. Land Co.	Fasken No. 1
502	Pan American Petroleum Corp.	David Fasken No. 1
503	C. E. Marsh	Barron No. 1-B
603	Blackwood & Nichols	B. L. Moss No. 1
64-502	Seaboard Oil of Delaware	Tillman No. 1
601	Shell Oil Co.	Price Bush Elkin No. 1
28-57-601	F. W. Holbrook & R. S. Brennard, Jr.	H. O. McAlister No. 1
602	Lone Star Producing Co.	L. B. Epley No. 2
58-401	do	Ida Mae Oldham No. 4-D
501	Mobil Oil Co.	Earl Powell No. 1
502	Cumberland & Weiner	Powell No. 1-4
702	Seaboard Oil Co. of Delaware	Hale No. 5-12
801	Mid-Continent Petroleum Corp.	Andrew Fasken No. 1
44-01-205	Gulf Oil Corp.	King No. 1-A
306	Phillips Petroleum Co.	Golladay No. 1-B
02-102	Coastal States Gas Producing Co.	A. Fasken No. 1-A
210	Amerada Petroleum Corp.	McClintic No. 30-1
211	do	McClintic No. 31-2
311	British American & Cabot Carbon	Bergstrom No. 1
511	Amerada Petroleum Corp.	O'Brien No. 43-2
512	do	O'Brien No. 6-6
701	Tex Harvey Oil Co.	Floyd No. 4-15
802	Amerada Petroleum Corp.	Dixon No. 1
803	do	K. S. Boone No. 4-18
804	do	K. S. Boone No. 3-18
09-703	Texaco Incorporated	Bryant No. 1-A

Table 8.-Oil and Gas Wells Used for Subsurface Control-Continued

Well	Operator	Lease and well
TJ-44-17-307	Blackwood & Nichols	Shackleford No. 1
406	Plymout'h Oil Co.	Midkiff No. 1
503	Sinclair Oil & Gas Co.	Herd-Midkiff No. 1-A
616	Humble Oil & Refining Co.	Lillie Midkiff No. 1-B
709	J. E. Jones Drilling Co.	Youngblood No. I-40
18-138	Mobil Oil Co.	Sam Preston No. 21
215	do	Bessie Freeman No. 3
426	Sinclair Oil & Gas Co.	T. 0. Midkiff No. 3
524	Mobil Oil Co.	D. T. Bowles No. 8
525	do	Sam R. Preston No. 3
526	Sinclair Oil & Gas Co.	Midkiff No. 59-G
611	Mobil Oil Co.	D. T. Bowles No. 17
715	Sinclair Oil & Gas Co.	Milo Palmer No. 1
827	do	Midkiff No. 36
45-06-302	Odessa Natural Gasoline Co.	Scharbauer No. 2-A
606	Lone Star Producing Co.	H. S. Foster No. 1
07-301	Standard Oil Co.	J. E. Simms No. 1
705	Texaco Incorporated	W. A. McKanles No.1
706	do	Scharbauer No. 1
08-402	G. H. Vaughn Producing Co.	Elsie & Clara Campbell No.1
14-308	Forest Oil Corp. & Cities Production Co.	Dora Roberts No. 3-B-l
904	do	Roberts No. 1-D
15-304	Mobil Oil Co.	Roy Parks No. 2
406	Vickers Exploration Co., Ltd.	Roy Parks No. 1
507	Mobil Oil Co.	Texaco incorporated No. 1-J
609	do	Roy Parks No. 16

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
TJ-45-15-708	Cities Service Petroleum Co.	Roberts Ranch Devonian Unit BF-22 No. 22
16-206	Pan American Petroleum Corp.	Jack B. Wilkinson No. 1
610	York & Harper, Inc.	Texaco Incorporated No. 1-A
904	Gulf Oil Corp.	Bryant No. 1-E
23-103	Forest Oil Corp.	Fee No. 1-45
203	Warren Petroleum Corp.	June T. Sanders No. 3
305	Sinclair Oil & Gas Co.	June Tippett No. 12-J
405	do	Sanders No. 12
503	do	June Tippett No. 9
606	do	June Tippett No. 15
607	do	June Tippett No. 3
608	do	June Tippett No. 1-A
707	do	June Sanders Tract B No. 2
708	General American, et al.	Peck No. 2-E
917	Phillips Petroleum Co.	Texaco Incorporated No. 2-BB
918	Mobil Oil Co.	Texaco Incorporated No. 1-0

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
UZ-44-18-917	El Paso Natural Gas	Weiner Floyd Midkiff Disposal No. 1
918	Pan American Petroleum Corp.	L. C. Proctor No. 1-C
19-707	do	L. C. Proctor No. 1-A
20-924	do	Myrtle McMaster No. 1
21-713	South Royalty Co.	O. N. Lane No. 1
26-305	Sinclair Oil & Gas	W. M. Wilde No. 8
612	General American Oil Co.	L. C. Proctor No. 1-B
27-407	Amerada Petroleum Corp.	G. L. Aldwell No. 1
620	Phillips Petroleum Co.	Malone No. 1
621	Cities Service Oil Co.	Merchant Heirs No. 2-15
622	Cities Production Corp.	Merchant No. 3-16
707	D. D. Strong, et al.	G. L. Aldwell No. 1-A
805	Orlando, et al.	G. L. Aldwell No. 2
28-104	Humble Oil & Refining Co.	Malone No. 1-C
206	MacDonald Oil Corp.	Malone No. 2
623	Sohio Petroleum Co.	E. G. Cauble No. 1-E
712	Mid-Continent Oil Co.	M. Forest No. 1
919	Pan American Petroleum Corp.	Rupert P. Ricker No. 1-H
29-106	do	Thomas E. Cook No. 1
205	Union Texas Petroleum Co.	Calvin H. Sugg No. 1-A
305	Standard Oil Co.	Calvin H. Sugg No. 1
407	Davison & Pembrook	Clarkson Estate No. 1
610	Spartan Drilling Co.	Calvin H. Sugg No. 1-142
719	Pan American Petroleum Corp.	T. R. Sowell No. 1-A
805	McGrath & Smith	Calvin H. Sugg No. 1-A
917	Devonian Co.	Calvin H. Sugg No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
UZ-44-29-918	Atlantic Richfield Co.	Calvin H. Sugg No. 1-137
30-106	Texaco Incorporated	Calvin H. Sugg No. 2
409	York & Harper, Inc.	Calvin H. Sugg No. 1
612	Mid-Continent Petroleum Corp.	T. R. Sowell No. 1
704	Atlantic Refining Co.	Calvin H. Sugg No. 1-B
805	Seaboard Oil Co.	Herbert Cope No. 1
34-303	Humble Oil & Refining Co.	Newmont Oil Co. No. 1-D
35-212	E. E. Fogelson	Frank Boyd No. 7-42
307	Southland Royalty	O. F. Boyd No. 2-5-B
607	Sinclair Oil & Gas Co.	Mrs. J. Weddell No. 1
703	Blackwood & Nichols	L. C. Clark No. 1
805	Phillips Petroleum Co.	S. A. Hartgrove No. 1
36-117	Skelly Oil Co.	Greenlee Heirs No. 2
214	Southwestern Natural Gas, Inc.	Greer Estate No. 1
316	Sohio Petroleum Co.	Katherine Trigg No. 2
508	Advance Petroleum Corp.	Hicks No. 1
509	Lindsey, et al.	Frank Lindley No. 1
617	Humble Oil & Refining Co.	S. E. Hughes No. 1
905	Blackwood & Nichols	D. E. Hughes No. 1
37-105	Humble Oil & Refining Co.	Sawyer No. 1-J
205	Union Texas Petroleum Co.	Calvin H. Sugg No. 1-C
308	do	Calvin H. Sugg No. 1-D
309	Texola Drilling Co., Inc.	Blakley No. 1-8-A
710	Humble Oil & Refining Co.	Zuletle Hughes No. 1-E
711	B. T. A. Oil Producers	Frances H. Crews No. 2
801	do	Rocker No. 3-B
802	do	652 Rocker No. 3-B

REAGAN COUNTY

Table 8.-Oil and Gas Wells Used for Subsurface Control-Continued

Well	Operator	Lease and well
uz-44-37-803	John L. Cox	Rocker No. 1-D-B
903	B. T. A. Oil Producers	661 Rocker No. 3-B
38-102	Union Texas Petroleum Co.	Calvin H. Sugg No. 3-D
304	Kern County Land Co.	Calvin H. Sugg No. 1
501	Humble Oil & Refining Co.	Sawyer No. 1-K
702	Jake L. Hamon	Rocker No. 2-A-B
703	do	Rocker No. 1-A-B
42-329	John Emch	Belcher No. 1
4 3-806	Sinclair Oil & Gas Co.	University Lands No. 1
4 4-308	Humble Oil & Refining Co.	Cynthia Malone No. 1
606	Gold Metals Consolidated Mining Co. & Santana Petroleum Corp.	Cynthia Malone, et al. No. 1
607	B. T. A. Oil Producers	Kewanee No. 1
608	Pan American Petroleum Corp.	University Lands No, l-BS
906	Hanley Oil Co.	University Lands No. l-C-10-9
45-106	John L. Cox	Cynthia Malone No. 1
205	Texola Drilling Co., Inc.	Rocker No. 1-71-T. P.-B
404	B. T. A. Oil Producers	Cynthia Malone No. 5-A-B
405	do	University Lands No. 2-MR T-N
506	Texas, Inc.	Becton No. 1
605	Texola Drilling Co.	Rocker No. 1-99-TP-B
810	Sunray DX Oil Co.	John 0. Carr No. 1
811	Texan Oil Co. & Green & Michaelson	Rocker No. 1-149-B
46-203	Humble Oil & Refining Co.	Sawyer Cattle Co. No. 1-D
502	do	W. A. Blakley No. 16
50-30 1	Cities Service Oil Co.	University Lands No. l-AX
51-103	Great Western Drilling Co.	University Lands No. l-AA

REAGAN COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
UZ-44-51-305	Big Lake Oil Co.	Santa Rita No. 13-C
206	Plymouth Oil Co.	University Lands No. 184
207	Continental Oil Co.	University Lands No. 63
306	Kerr-McGee Oil Industries, Inc.	University Lands No. 1-C
803	North Star Oil Corp.	Texas Gulf-University Lands No. 1
904	W. E. Bakke	Do.
905	Rodger Harris	Wiggins-Hyde No. 1
52-605	Union Oil Co.	University Lands No. 1-76
53-206	do	John R. Scott No. 2-D
207	Texas Gulf Production Co.	Isy Schwartz No. 1
303	J. P. Williams, et al.	John R. Scott No. 1
304	W. L. Meadows, Jr.	Scott No. 1
404	Continental Oil Co.	University Lands No. 1-7SWI
410	Yeatman Drilling Co.	University Lands No. 2
507	Lipan Oil Co. & Russell Maguire	R. A. Wolters, et al. No. 1
706	do	University Lands No. 1-31
803	Continental Oil Co.	University Lands No. 1-3
807	Lipan Oil Co.	R. A. Wolters No. 1-1-1
903	H. L. Albaugh	University Lands No. 1-2-49
54-301	Bankline Oil Co.	Bankline Branch No. 1
504	Amerada Petroleum Co.	Ella Owens No. 5
712	do	N. W. Hickman No. 2
903	Jay H. Floyd	T. J. Murphy No. 1
904	Clyde Hurst	University Lands No. 1-CH
59-301	Continental Oil Co.	University Lands No. 7-1
60-101	W. D. Anderson & Sons	University Lands No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
UZ-44-60-301	Ross Brunner	University Lands No. 1-12
61-301	Plymouth Oil Co.	University Lands No. 1-A
62-202	Atlantic Refining Co.	University Lands No. 1-48-C

REAL COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
WA-69-01-102	Woodward & Co.	H. & C. Peterson
301	Sun Oil Co.	Oppenheimer & Dietert
03-505	Eastland Oil Co.	A. D. Auld
10-601	Pan American Petroleum Corp.	G. O. Knippa
11-301	Moore Exploration Co.	Claude Haby

SCHLEICHER COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
WY-43-57-902	Bobby Manziel	University Lands No. 1
58-607	Pure Oil Co.	R. S. Williams No. 1
59-406	Pan American Petroleum Corp.	Do.
606	Delta Gulf Drilling Co. & W. H. Hunt	R. L. Henderson No. 1
809	Renwar & Delta Gulf Drilling Co.	D. E. Delong No. 1
60-504	Wesley W. West	Christina Mittel No. 2
606	Sinclair Oil & Gas Co.	S. J. Hall No. 1
607	Edwin L. Cox	J. F. Runge No. 2
61-606	Gray Wolfe Co.	Margaret W. Hicks No. 1
62-406	J. R. McDermott & Tucker Drilling Co.	A. B. Thomerson No. 1
504	Tucker Drilling & Jones & Lyons	Pat Jackson No. 1
708	Cosden Petroleum Corp. & Fortune Drilling Corp.	Jim O'Harrow No. 2
63-807	Sinclair Oil & Gas Co.	Lawrence Ruff No. 1
55-02-416	Cities Service Oil Co.	University Lands No. 1-BM
818	Continental Oil Co.	H. G. Moore No. 1
03-211	Gulf Oil Corp.	E. F. Sauer Gas Unit No. 1
709	Texas Crude Oil Co.	N. Daughdrill No. 1
04-105	do	T. C. Meador No. 1
310	Pan American Productions Co.	H. F. Thomson No. 1
311	Sinclair Oil & Gas Co.	J. B. McClatchy No. 4
312	do	McClatchey No. 5
904	Cities Service Oil Co.	Meador No. 1-A
05-111	Sinclair Oil Co.	M. F. McClatchy No. 1
06-404	Ralph Lowe	M. M. Reynolds No. 1
405	Fortune Production Co.	Luke Robinson No. 1
07-507	Lone Star Producing Co.	R. H. Martin No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
WY-55-07-906	El Paso Natural Gas	John Treadwell No. 1
09-605	Dual Production Co.	Powell No. 1
11-413	Humble Oil & Refining Co.	S. L. Stamford No. 1
12-101	Pan American Petroleum Corp.	A. West No. 1
506	Moss Petroleum Co. & Tucker Drilling Co. & L. E. Scherck	Thad A. Thompson No. 1-A
13-212	Humble Oil & Refining	Jess Koy No. 1
706	Tucker Drilling Co.	Bert Page No. 1
14-101	Bryson Oil & Gas & W. Carl Proctor & Magnus Oil Corp.	Judkins-Spencer No. 1
301	Tex-Tor Oil Corp.	Do.
405	C. L. Norsworthy, Jr.	Mary McBurnett No. 1
507	G. W. Strake	Judkins No. 1-C
908	Texaco Incorporated	Judkins No. 1-A
15-210	Sinclair Oil & Gas Co.	Virgil Powell No. 2-B
211	do	V. J. & J. D. Powell No. 2
18-102	Delta Gulf Drilling Co. & Cabot Carbon Co.	Sol Mayer No. 1
20-206	Sinclair Oil & Gas Co.	Margaret D. Thomson No. 1
23-308	Mobil Oil Co.	Mary Ball No. 1

STERLING COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
XP-28-62-610	Humble Oil & Refining Co.	W. N. Reed No. 1-B
901	Ray A. Albaugh	Reed No. 1
63-507	Sunset International Petroleum Corp.	Sellers No. 1-174
508	Shaheen & Son	Sellers No. 2-175
609	Cosden Petroleum Corp.	Parramore No. 2
905	Ike W. Lovelady	Parramore No. 1
29-57-704	Manhatten	E. H. Wood No. 1
43-02-105	John J. Eisner	Knight No. 3
09-112	California Co.	Davis No. 3-1
406	Johnson & Fullick	J. T. Davis No. 1
502	Sun Oil Co.	Fay Hildebrand No. 1
807	Texaco Incorporated	Foster No. 1
10-108	C. J. Wrightman	Claude Collins No. 1
411	Alvon Oil & Gas Co., Midwest Oil Corp. & Lion Oil Co.	Claude Collins, Jr. No. 1
801	Sun Oil Co.	B. L. Stringer No. 2
17-204	Humble Oil & Refining Co.	Mrs. Dayvault No. 1
603	Kanawha-Angelo Oil Co.	L. T. Clark No. 1
801	Duncan Drilling Co.	Harris No. 1
44-07-402	Ray Morris Drilling Co.	W. N. Reed, et al. No. 1
501	Sam D. Ares	George McIntire No. 1
503	J. P. "Bum" Gibbins, Inc.	McIntire No. 1
601	Humble Oil & Refining Co.	G. H. McIntire No. 1
14-607	Amerada Petroleum Corp.	Texaco Incorporated No. 1-E
608	Foster	Glass No. 6
15-401	Texaco Incorporated	Sterling No. 31-B
403	Marathon Oil Co.	Glass No. 3-A

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
XP-44-15-404	Marathon Oil Co.	Texaco Incorporated No. 4-C
502	H. M. H. Operators	Ray No. 1
503	Bay Petroleum Co.	Bade No. 1-B
701	Sun Ray DX Oil Corp.	Glass No. 1
16-406	H. M. H. Operators	Foster No. 2
502	Amerada Petroleum Corp.	McDonald No. 1
504	Abco Oil Co.	Ona Davis No. 9
603	Norfitt Petroleum Co.	Durham No. 1
23-402	Honolulu Oil Corp.	Cope No. 1-A
24-103	Champlin Oil & Refining Co.	Foster Conger No. 2
407	Champlin Petroleum Co.	R. T. Foster No. 1
504	Champlin Petroleum Co. & W. A. Moncrief	Horwood-Hilderbrand No. 1-36
705	Shell Oil Co.	Shell Hildebrand No. 2
30-301	McElroy Ranch Co., et al.	C. H. Sugg No. 1
613	Honolulu Oil Corp.	Cope No. 7

SUTTON COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
XS-55-19-401	Tennessee Production Co.	Alice L. Jones No. 1
603	Sinclair Oil & Gas Co.	Christina Mittel No. 1
704	El Paso Natural Gas	Rose Thorp No. 1
806	do	Meckel No. 2
807	do	Meckel No. 1-D
808	do	Meckel No. 3-B
905	do	B. F. Meckel No. 1-A
906	do	Meckel No. 3-B
20-404	C. L. Norsworthy & Lone Star Gas Co.	Thomson No. 7
405	Sinclair Oil & Gas Co.	R. M. Thomson No. 1
406	C. L. Norsworthy & Lone Star Gas Co.	Do.
505	El Paso Natural Gas	Thomson No. 1-B
603	do	Joe Logan No. 1
702	do	Thompson No. 1-C
703	do	Steen No. 4
704	do	Steen No. 3
705	do	Steen No. 2
706	do	Steen No. 1
808	Pure Oil Co.	Ida Behling No. 1
21-703	C. L. Norsworthy, Jr.	R. A. Halbert No. 1
22-401	Humble Oil & Refining Co.	Stella Lloyd No. 1
25-801	J. B. Moorhead	W. F. Berger
26-204	El Paso Natural Gas	E. S. Mayer No. 1
508	Texas American Oil Co. & Sinclair Oil & Gas Co.	Mayfield No. 1-A
603	do	El Paso Blk. 133 No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
XS-55-27-107	El Paso Natural Gas	DeBerry No. 9-A
207	do	DeBerry No. 4-A
303	do	Davis No. 1-E
502	do	Davis No. 1-D
503	do	E. M. DeBerry No. 1
610	Ada Oil Co.	Rip Ward No. 1
905	Pioneer Production Corp.	H. Fields No. 2
28-110	Pan American Petroleum Corp.	Miers No. 3-A
29-306	Gulf Oil Corp.	G. C. Allison No. 1
401	Texas Gulf Producing Co.	Allison No. 1
703	C. L. Norsworthy	Sam Allison No. 1
30-305	Paul Teas	Mower No. 1
31-102	Phillips Petroleum Co.	Reiley No. 1
404	Mayfair Minerals, Inc.	C. D. Wyatt
703	Hunt Oil Co.	Carnie Wyatt No. 1
34-802	Shell-Sinclair	Aldwell Brothers No. 1
35-204	Delta Drilling Co. & Pauley Petroleum, Inc.	Sawyer No. 1
308	El Paso Natural Gas	C. Shurley No. 1
36-804	Pan American Petroleum Corp.	Thelma Espy No. 1
37-104	Pure Oil Co.	S. H. Allison No. 1
801	Phillips Petroleum Co.	Libb No. 1-A
38-807	Wesley West	Williamson County School Land No. 1
39-604	Bill Holland	J. T. Rieck No. 1
706	Shell Oil Co.	S. B. Roberts No. 1
41-304	Mallard Petroleum, Inc.	Aldwell No. 1
42-104	Amerada Petroleum Corp.	Winne Aldwell Estate No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
XS-55-43-304	John J. Eisner	Mack O. Cauthorn No. 1
44-601	Ray Morris Drilling Co.	D. J. Harrison No. 1
47-603	Nelson & Mellard	O. W. Cardwell No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
YB-43-18-702	O. E. Schkade	W. C. Weddell No. 3
805	Moore Exploration Co.	E. C. Rawlins No. 1
26-503	E. H. Cox	Funk No. 1
908	Texas Co.	P. W. Turner No. 1
43-601	Sinclair Oil & Gas Co.	M. D. Bryant No. 1-6
51-202	Lipan Oil Co.	Mrs. W. A. Guinn No. 18
203	Texota Oil Co.	Jones No. 4
306	American Republic Corp. & J. K. Dorrance	Charles Atkinson No. 2-A
605	Royal Drilling Co. & Cumberland	Moss No. 1
805	Chase Petroleum Co.	Winterbotham No. 1-A
907	do	Winterbotham No. 1
52-407	J. K. Dorrance Trustee	C. D. & C. L. Atkins No. 1
501	C. L. Norsworthy, Jr.	J. D. Robertson No. 1-A
53-307	Pan American Petroleum Corp.	J. W. Johnson No. 3-A
408	American Republic Corp.	Harrington No. 1
54-204	Ada Oil Co.	J. W. Johnson, Jr. No. 1
703	Phillips Petroleum Co.	Griffith No. 1-A
55-601	Amerada Petroleum Co.	Joan C. Denis No. 1
62-102	Sinclair Oil & Gas Co.	R. L. Stansberry No. 1

UPTON COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control

Well	Operator	Lease and well
YL-44-17-904	Humble Oil & Refining Co.	Shackelford No. 3-B
905	do	Shackelford No. 2-B
18-716	Sinclair Oil & Gas Co.	Midkiff No. 58-E
717	do	Midkiff No. 52-F
830	Amerada Petroleum Co.	Elkins No. 4-19
831	Sinclair Oil & Gas Co.	Midkiff No. 28
25-106	Paul L. Davis	Windham No. 1-9
203	J. E. Jones Drilling Co.	G. E. Atkins No. 1-14
304	Humble Oil & Refining Co.	Tippett No. 1
403	R. B. Stallworth, Jr., et al.	Rutter & Wilbanks No. 2
506	B. L. McFarland Drilling Contractors	Cowden No. 1-37
603	Amerada Petroleum Co.	Tippett No. 1-44
905	do	Horby No. 1
26-115	Gustave Ring	Tippett No. 2-22-B
201	Cameron & Simmons	Elkin No. 1-29
214	Amerada Petroleum Corp.	L. B. Elkin No. 2-30
215	do	Lula B. Elkins No. 1-31
405	do	Tippett No. 2-46
406	Phillips Petroleum Co.	Tippett No. 10-A
407	Amerada Petroleum Corp.	V. P. Tippett No. 1-2
521	Phillips Petroleum Co.	Tippett No. 4-B
522	Sinclair Oil & Gas	J. E. Hill No. 1
602	Ashland Oil & Refining Co.	Sherrod No. 1
33-602	Barnett Sears & Young	Weeks No. 1
901	J. C. Maxwell	H. F. Neal No. 1
34-103	Mobil Oil Co.	Ryburn No. 1
403	Humble Oil & Refining Co.	Z. Oswalt, et al. No. 1

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
YL-44-34-602	James G. Brown & Assoc.	Halff Estate No. 1-A
804	Blackwood & Nichols	Humble-Barnett No. 1
809	James G. Brown & Assoc.	J. D. Cristy No. 1
919	Hiawatha Oil & Gas Co.	Rosa Barnett No. 1
41-201	Hunt Oil Co.	Henry Cravens No. 1
42-103	D. D. Feldman, et al.	Max Pray State No. 1
205	Sinclair Oil & Gas Co.	Elliott No. 2-C
502	C. U. Bay	University Lands No. 1
503	Hewgley Drilling Co.	Do.
504	Plymouth Oil Co.	Neal No. 1-8
49-212	Samedan Oil Co.	Neal No. 1
50-104	Texaco Incorporated	University Lands No. 1-DG
202	Cities Service Oil Co.	University Lands No. 1-A-H
702	Gulf Oil Corp.	University Lands No. 1-E-ER
57-103	Sinclair Oil & Gas Co.	J. L. Nutt No. 1
104	Gustave Ring	Noelke No. 1
105	Woodward & Co.	Corbett No. 1
106	Cities Service Oil Co.	Noelke No. 1-B
107	Garrett, Wynne & Black	Sue Noelke Houser No. 1
108	W. R. Goddard	Avery No. 1
45-23-903	Mobil Oil Co.	T. R. Wilson No. 42-15
30-902	Gulf Oil Corp.	McElroy Ranch No. 4-B-F
31-305	Texaco Incorporated	Upton No. 1-L-Fee
504	Bill Roden, et al.	Texaco Incorporated No. 1
505	Sinclair Oil & Gas Co.	Do.
803	do	J. P. Rankin No. 1
32-102	Magnolia Petroleum Co.	American Republic No. 2-A

Table 8.-Oil and Gas Wells Used for Subsurface Control-Continued

Well	Operator	Lease and well
YL-45-32-204	J. J. August & J. Roy Derrick	Windham No. 1
402	Vickers Exploration Ltd.	Powell No. 1
602	Seaboard Oil Co.	Meiners No. 1
702	Josephine P. Bay	V. J. Powell No. 3-B
804	Sunray Mid-Continent	Hazel Neal No. 2-A
39-101	Gulf Oil Corp.	McElroy Ranch No. 2-H
202	Sinclair Oil & Gas Co.	McElroy No. 6
503	Wilshire Oil Co.	McElroy No. 31-130
504	do	McElroy No. 42A-135
505	do	McElroy No. 14-117
506	do	McElroy No. 14-130
507	Sinclair Oil & Gas Co.	McElroy No. 2
602	Humble Oil & Refining Co.	McElroy Ranch No. 1-B
603	Wilshire Oil Co.	Windham No. 23-I 18
805	Sinclair Oil & Gas Co.	Windham No. 5
905	Wilshire Oil Co.	McElroy No. 13-119
906	Greenbrier Oil Co.	Windham No. 1
907	Gulf Oil Corp.	Ethel Jackson, et al. No. 1
40-103	Texaco Incorporated	Hazel Neal No. 1
104	Sunray Mid-Continent	Do.
204	Texaco Incorporated	J. H. Graf No. 3-(NCT-4)
16-302	Albert C. Bruce, Jr.	M. G. Damron No. 2
303	do	J. T. McElroy No. 1
901	Edwin L. Cox	Gentry No. 1
47-103	Albert C. Bruce	A. J. Sabo No. 1
202	Sinclair Oil & Gas Co.	S. A. Windham No. 1
203	do	Eddleman No. 1

UPTON COUNTY

Table 8.—Oil and Gas Wells Used for Subsurface Control—Continued

Well	Operator	Lease and well
YL-45-47-506	Humble Oil & Refining Co.	Rosa H. Barnett No. 5-D
703	Lone Star Producing Co.	Jacobs Livestock No. 1-B
802	Texas Pacific Coal & Oil Co.	W. W. McClure No. 2-acct. No. 1
803	do	W. W. McClure No. 7-acct. No. 1
904	Gulf Oil Corp.	Ernestine Freeman No. 2-E
905	Mobil Oil Co.	Halff Interests No. 1
48-103	Hunt Oil Co.	V. T. Amacker No. 1-62
504	Gulf Oil Corp.	C. M. Bell No. 1
54-502	Buffalo Oil Co.	Sanger Investment Co. No. 1
55-102	James G. Brown & Assoc.	King Ranch Oil & Lignite Co. No. 1-A
203	Gulf Oil Corp.	A. J. Herrington No. 6-(Tract-A)
302	Odessa Natural Gasoline Co.	J. H. Shirk Estate No. 1
303	Neville G. Penrose, Inc.	King Ranch Oil & Lignite Co. No. 1
405	Tennessee Gas & Trans Co.	M. L. Baker No. 11
604	Amerada Petroleum Corp.	Lee R. Lane No. 3
605	Gulf Oil Corp.	J. H. Shirk No. 28-E
56-102	Levin, Patton, et al.	F. Campbell No. 1
304	Standard Oil Co.	C. S. Stevenson No. 1