TEXAS WATER DEVELOPMENT BOARD

REPORT 51

# RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE COLORADO RIVER BASIN, TEXAS

By

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of these additional studies have been initiated as a result of the findings of this reconnaissance investigation.

Previously published reports on ground-water reconnaissance investigations include:

Texas Board of Water Engineers Bulletin 6016,
"Reconnaissance Investigation of the Ground-Water Resources of the Canadian River Basin, Texas." (out of print)

Texas Water Commission Bulletin 6305,
"Reconnaissance Investigation of the Ground-Water Resources of the Gulf Coast Region, Texas." (out of print)

Texas Water Commission Bulletin 6306,
"Reconnaissance Investigation of the Ground-Water Resources of the Red River, Sulphur River, and Cypress Creek Basins, Texas."

Texas Water Commission Bulletin 6307,
"Reconnaissance Investigation of the Ground-Water Resources of the Sabine River Basin, Texas."

Texas Water Commission Bulletin 6308,
"Reconnaissance Investigation of the Ground-Water Resources of the Neches River Basin, Texas."

Texas Water Commission Bulletin 6309,
"Reconnaissance Investigation of the Ground-Water Resources of the Trinity River Basin, Texas."

Texas Water Commission Bulletin 6310,
"Reconnaissance Investigation of the Ground-Water Resources of the Brazos River Basin, Texas." (out of print)

Texas Water Commission Bulletin 6409,
"Reconnaissance Investigation of the Ground-Water Resources of the Guadalupe, San Antonio, and Nueces River Basins, Texas."

Texas Water Commission Bulletin 6502,
"Reconnaissance Investigations of the Ground-Water Resources of the Rio Grande Basin, Texas." (a 3-volume report)

Texas Water Development Board

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## FOREWORD

Ground-water reconnaissance studies are the first phase of the State's water-resources planning concerning ground water as outlined in the progress report to the Fifty-Sixth Legislature titled "Texas Water Resources Planning at the End of the Year 1958." Before an adequate planning program for the development of the State's water resources could be prepared, it was necessary to determine the general chemical quality of the water, the order of magnitude of ground-water supplies potentially available from the principal water-bearing formations of the State, and how much of the supply is presently being used. To provide the data necessary to evaluate the ground-water resources of Texas, reconnaissance investigations were conducted throughout the State under a cooperative agreement with the U.S. Geological Survey. The ground-water reconnaissance investigations were conducted by river basins so that the results could be integrated with information on surface water in planning the development of the State's water resources. The river basins of the State were divided between the Ground Water Division of the then Texas Water Commission and the U.S. Geological Survey for the purpose of conducting and reporting on the results of the ground-water investigations.

On September 1, 1965 the Texas Water Commission (formerly, before February 1962, the State Board of Water Engineers) experienced a far-reaching realignment of functions and personnel, directed toward the increased emphasis needed for planning and development Texas' water resources and for administering water rights. Realigned and concentrated in the Texas Water Development Board were the investigative, planning, development, research, financing, and supporting functions, including the reports review and publication functions. The name Texas Water Commission was changed to Texas Water Rights Commission, and responsibility for functions relating to water-rights administration was vested therein.

For the reader's convenience, references in this report have been altered, where necessary, to reflect the current (post-September 1, 1965) assignment of responsibility for the function mentioned. In other words credit for a function performed by the Texas Water Commission before the September 1, 1965 realignment generally will be given in this report either to the Water Development Board or to the Water Rights Commission, depending on which agency now has responsibility for that function.

This report presents the results of the Colorado River basin ground-water reconnaissance investigation. It provides a generalized evaluation of the ground-water conditions in the basin and points out areas where detailed studies and continuing observations are necessary. These additional studies will be required to provide estimates of the quantity of ground water available for development in smaller areas, to provide more information on changes in chemical quality that may affect the quantity of fresh water available for development, and to better determine the affects of present and future pumpage. Some

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# RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE COLORADO RIVER BASIN, TEXAS


## ABSTRACT

The reconnaissance investigation of the Colorado River basin in Texas was undertaken as part of a statewide program designed to provide the general order of magnitude of ground-water supplies potentially available from the principal water-bearing formations of Texas. The Colorado River basin extends across the central part of the State and covers approximately 40,440 square miles. The area of study includes all or parts of 64 counties and represents about 15.3 percent of the total land-surface area of Texas.

The physiographic expression of the Colorado River basin ranges from flat treeless plains to rugged hills with altitudes ranging from sea level at the mouth of the Colorado River to about 4,000 feet above mean sea level at the New Mexico-Texas State line. The average annual precipitation ranges from less than 15 inches at the upper end of the basin to more than 40 inches near the coast. The population within the Colorado River basin in 1960 was approximately 758,000, nearly 8 percent of the State's population. The economy of the basin is primarily based on varying forms of agriculture. Oil and gas production scattered throughout the basin also contributes to the economy.

Two primary aquifers in the Colorado River basin are capable of supplying large quantities of water over large areas of the basin. These are the Ogallala and the Edwards-Trinity (Plateau) aquifers. Six aquifers are classified as secondary since they are capable of supplying large quantities of water over relatively small areas. These are the Edwards-Trinity (High Plains), the Santa Rosa, the Ellenburger-San Saba, the Hickory, the Gulf Coast, and the Carrizo-Wilcox aquifers. In addition to the primary and secondary aquifers, other aquifers yield small to moderate quantities of water locally, but have limited potential. These are aquifers of the Chinle Formation, Cretaceous rocks (outliers), alluvium, Permian rocks, Pennsylvanian rocks, Welge Sandstone Member of the Wilberns Formation, Precambrian rocks, Trinity Group (North-Central Texas), Edwards Limestone (Balcones fault zone), Queen City Formation, Yegua Formation, and Jackson Group.

On the order of 30,000,000 to 50,000,000 acre-feet of ground water of a chemical quality suitable for most municipal, industrial, and irrigation uses is estimated to be available from storage in primary and secondary aquifers of the Colorado River basin. Of this amount, 15,000,000 to 20,000,000 acre-feet is estimated to be available from storage in the Ogallala aquifer. On the order of 300,000 to 400,000 acre-feet of ground water per year is available from primary and secondary aquifers on a perennial basis. Of this amount,

150,000 to 200,000 acre-feet per year is estimated to be available from the Edwards-Trinity (Plateau) aquifer.

In 1960, approximately 820,000 acre-feet of ground water was pumped from the aquifers of the Colorado River basin for municipal, industrial, and irrigation purposes. Most of that pumpage, about 690,000 acre-feet, was from the Ogallala aquifer. Water levels are declining in the Ogallala and Edwards-Trinity (Plateau) aquifers in areas of heavy pumping.

For detailed water planning or for planning individual water supplies, more detailed information than is contained in this report is needed. Detailed ground-water investigations, as outlined in the progress report to the Fifty-Sixth Legislature titled "Texas Water Resources Planning at the End of the Year 1958," should be made on the primary and secondary aquifers of the Colorado River basin to better define the geologic and water-bearing characteristics of the aquifers and to refine the estimates presented in this report of ground water available for development.

# RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE COLORADO RIVER BASIN, TEXAS

## INTRODUCTION

### Purpose and Scope

The reconnaissance of the Colorado River basin was made as part of a statewide program to determine the order of magnitude of ground-water supplies potentially available from principal water-bearing formations in the State.

The approach to water planning in Texas is by river basins; thus, the ground-water reconnaissance investigations were conducted by river basins so that the results could be integrated with information on surface water by agencies and groups concerned with planning the development of the State's water resources. To facilitate these ground-water reconnaissance studies, the State was divided into 13 major river basin areas and a coastal region which includes all or parts of several river basins and their intervening coastal areas. In planning the development of the State's water resources to meet present and future needs, the quantities of ground water and surface water that can be developed must be known and considered. Because adequate information was lacking for determining the total quantity of ground water available for development in much of the State, the Texas Water Commission recommended in a report to the Fifty-Sixth Legislature that ground-water reconnaissance studies be made.

The reconnaissance investigation of the Colorado River basin included determinations of the location and extent of the principal water-bearing formations within the basin, the general chemical quality of ground water available, the order of magnitude of ground-water supplies potentially available for development, and the extent of the present development of these supplies. The results of the Colorado River basin reconnaissance investigation provide a generalized evaluation of ground-water conditions throughout the basin. The amount of water available for development in the Colorado River basin determined during this study probably is correct in its order of magnitude but cannot be considered an exact figure. Results of the investigation are not sufficiently specific for detailed water planning or for the planning of individual water supplies. This report points out areas where detailed studies and continuing observations are necessary to determine the quantity of ground water available for development in specific areas, to provide more information on changes in chemical quality that may affect the quantity of fresh ground water available for development, and to better determine the effects of present and future pumpage.

## Location and Extent

The Colorado River basin of Texas is located in the central part of the State, as shown by Figure 1. It extends northwesterly from the Gulf Coast on the south to the Texas-New Mexico State line on the west and includes the areas in Texas drained by the Colorado River and its tributaries. The area within the Colorado River basin in Texas is approximately 40,440 square miles, or about 15.3 percent of the State's total land-surface area. Approximately 10,000 square miles of the western part of the basin in Texas is noncontributing in respect to surface runoff into the Colorado River, as is the 1,870 square miles in the upper reaches of the Colorado River basin in New Mexico. The Colorado River basin in Texas includes all or parts of 64 counties.

The vast size and varying physiographic conditions necessitated the division of this basin into three regions (Figure 1) in order to facilitate the compilation of this ground-water inventory. Each of the three regions contains its series of principal water-bearing formations and, in most instances, a different type of geologic, topographic, and economic conditions. The boundaries of these regions coincide with the topographic limits of the Colorado River basin as well as those of smaller drainage subdivisions which have been defined by the Water Development Board.

## Methods of Investigation

This investigation was started in October 1959. The fieldwork was concluded in September 1961. During the course of this study, special emphasis was placed on the following items:

1. Collection and compilation of readily available logs of wells and preparation of generalized cross sections and maps showing other subsurface geologic data.

2. Inventory of large wells and springs, and major pumpage.

3. Compilation of existing chemical analyses and sampling of water from selected wells for additional analyses.

4. Determination of areas of recharge and discharge for the principal water-bearing formations.

5. Obtaining pumping-test data on selected wells to determine the water-bearing characteristics of the principal water-bearing formations.

6. Correlation and analysis of all data to determine the order of magnitude of ground-water supplies available for development and the general effects of present and future development of these supplies.

The basic data used in the preparation of this report have been compiled in tabular form and placed in the files of the Texas Water Development Board at Austin, Texas.

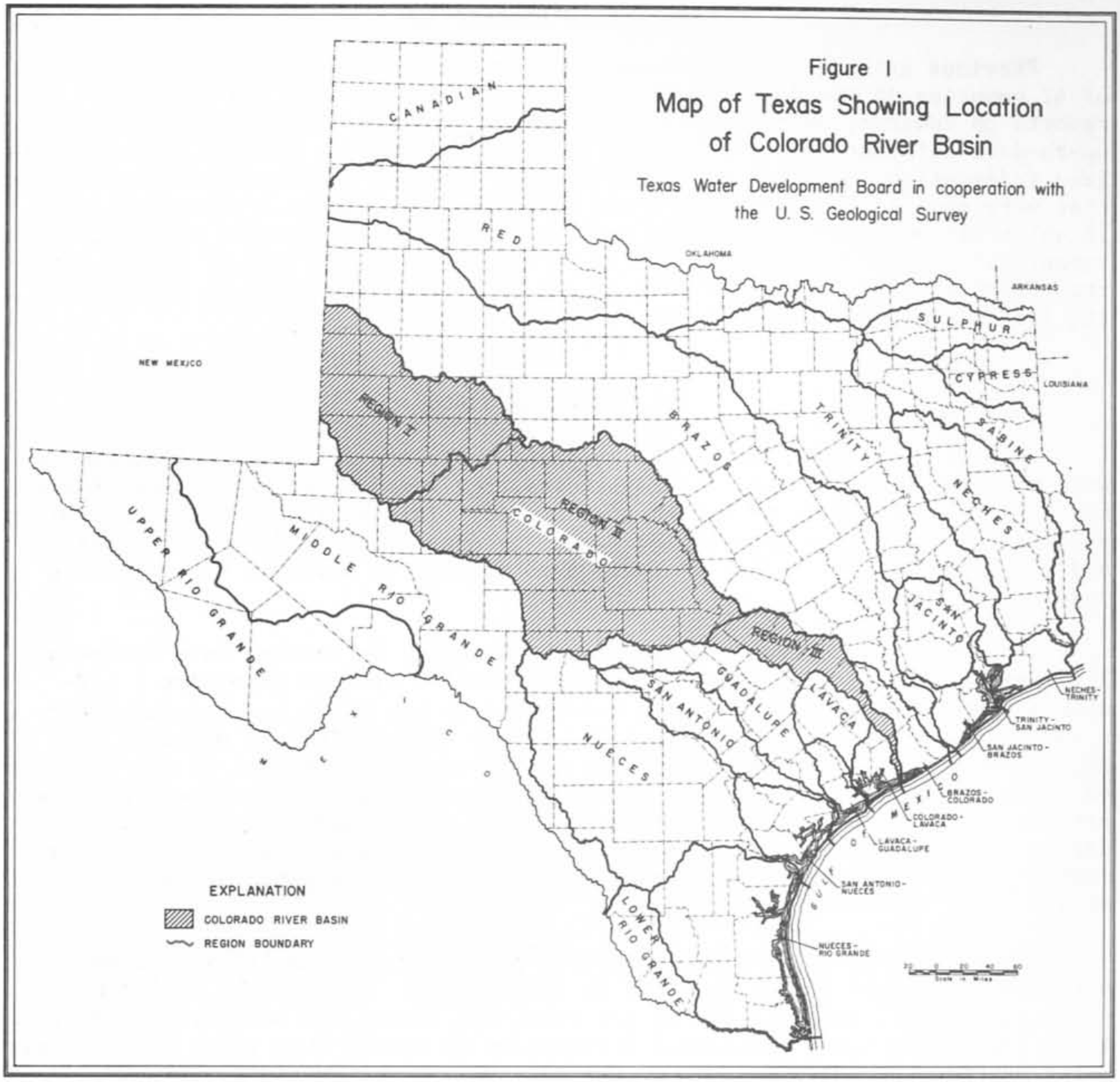



Figure 1
Map of Texas Showing Location of Colorado River Basin
Texas Water Development Board in cooperation with the U. S. Geological Survey

## Previous Investigations

Previous ground-water investigations have been conducted in all or parts of 42 counties in the Colorado River basin. Of these, only the published reports on Edwards, Hays, McCulloch, and Real Counties provide comprehensive up-to-date information. The results of the other studies provide some generalized information, such as that obtained from a number of water-well inventories that were made in the late 1930's and early 1940's. Figure 2 shows the areas in which ground-water studies had been made prior to the present reconnaissance investigation, and the general nature of such studies. A list of ground-water reports pertaining to earlier work in the Colorado River basin is included in the list of references at the end of this report.

## Well-Numbering System

In order to facilitate the location of wells and to avoid duplication of well numbers in present and future studies, the Texas Water Development Board has adopted a statewide well-numbering system. This system is based on division of the State into quadrangles formed by degrees of latitude and longitude and the repeated subdivision of these quadrangles, as shown on the following page.

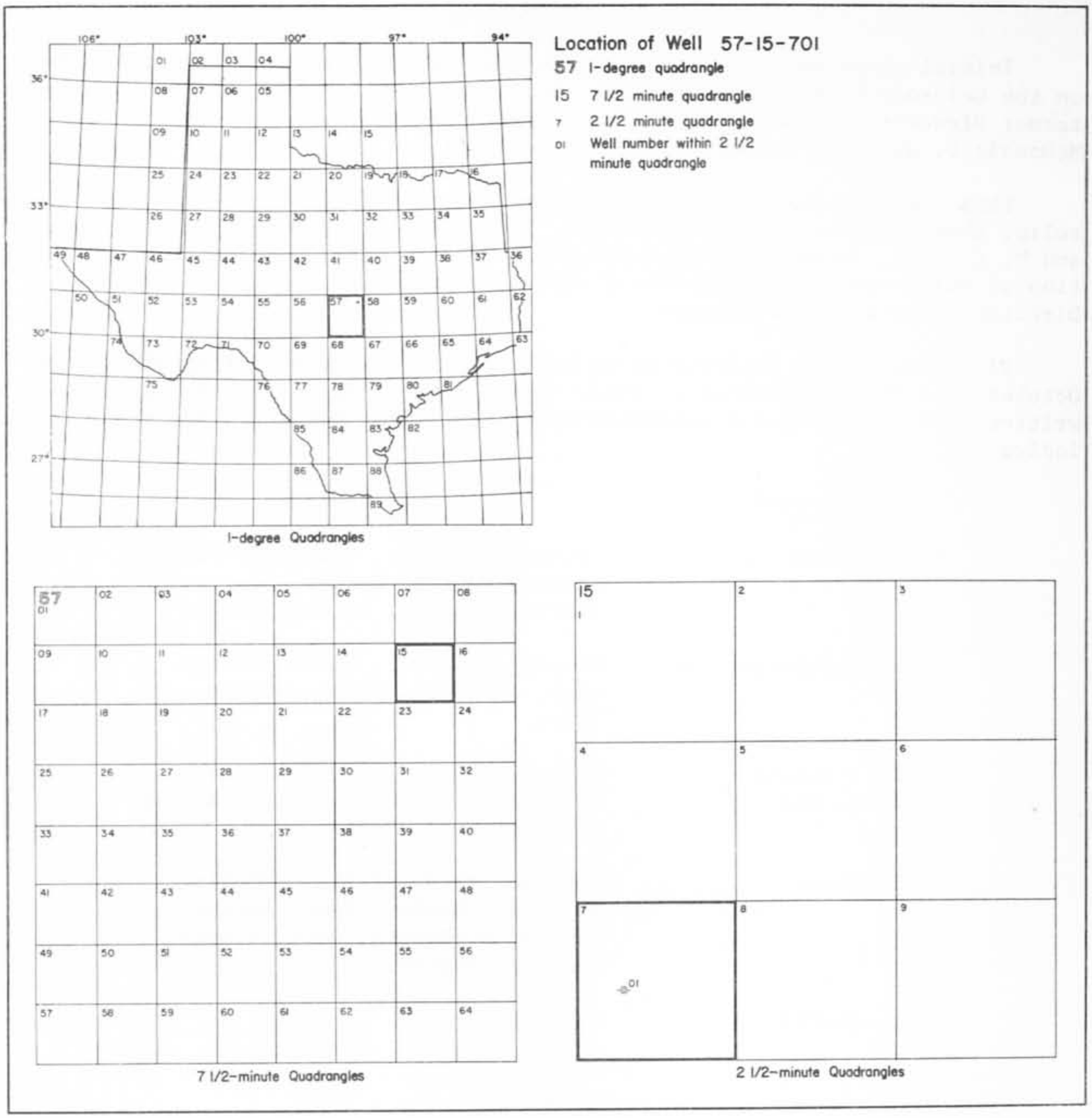
The largest quadrangle, a 1-degree quadrangle, is divided into sixty-four 7 1/2-minute quadrangles, each of which is further divided into nine 2 1/2-minute quadrangles. Each 1-degree quadrangle in the State has been assigned a number for identification. The 7 1/2-minute quadrangles are numbered consectively from left to right beginning in the upper left corner of the 1-degree quadrangle, and the 2 1/2-minute quadrangles within the 7 1/2-minute quadrangle are similarly numbered. The first 2 digits of a well number identify the 1-degree quadrangle; the 3rd and 4th, the 7 1/2-minute quadrangle; the 5th digit identifies the 2 1/2-minute quadrangle; and the last 2 digits identify the well within the 2 1/2-minute quadrangle.

The individual wells used as control points on various illustrations have not been identified by well numbers in this report. However, by utilizing the 7 1/2-minute grid system shown on the maps, the reader can adequately identify the wells in the event additional information is needed from files of the Texas Water Development Board.

## Acknowledgements

The reconnaissance studies were greatly facilitated by the aid and cooperation given by many individuals and organizations. Appreciation is expressed to the well drillers; consultants; officials of many municipalities, industries, utility companies, governmental agencies, underground water conservation districts, and geological societies; and water well owners for their cooperation and contribution of data. Appreciation is also expressed to the many oil companies who not only supplied data on their water supplies, but also permitted the use of numerous mechanical well logs from their files.

Special acknowledgement is made to personnel of the U.S. Geological Survey for the data they furnished on parts of the Colorado River basin. Grateful acknowledgement is expressed to William F. Guyton and Associates, consulting ground-water hydrologists, for their review and comments on this report.


Location of Well 57-15-701
57 1-degree quadrangle
15 7 1/2 minute quadrangle
7 2 1/2 minute quadrangle
01 Well number within 2 1/2 minute quadrangle
106°
103°
100°
97°
94°
36°
33°
30°
27°
1-degree Quadrangles
7 1/2-minute Quadrangles
2 1/2-minute Quadrangles

## Personnel

Initial planning for the reconnaissance fieldwork and the resulting report on the Colorado River basin was done under the direction of L. G. McMillion, former Director, Ground Water Division, and under the general direction of McDonald D. Weinert, former Chief Engineer.

This investigation was made under the general direction of John J. Vandertulip, Chief Engineer; L. G. McMillion, former Director, Ground Water Division; and M. L. Klug, former Assistant Director, Ground Water Division. The preparation of this report was under the direct supervision of Richard C. Peckham, Director, Ground Water Division.

Fieldwork in the Colorado River basin was accomplished during the period October 1, 1959 to September 1, 1961. Basic data, from which this report was written, were obtained and assembled by the following personnel for the areas indicated:

| Personnel | Counties worked |
|---|---|
| F. A. Rayner | Cochran, Hockley, Yoakum, Terry, Gaines, Dawson, Borden, Scurry, Andrews, Martin, Ector, Midland |
| V. M. Shamburger, Jr. | Howard, Mitchell, Nolan, Glasscock, Sterling, Upton, Reagan, Irion |
| J. B. Wesselman<br>J. T. Goodier | Coke, Runnels, Tom Green, Concho, Schleicher, Menard, Sutton, Kimble, Edwards, Kerr, Real |
| J. R. Mount | Coleman, Brown, Mills, McCulloch, San Saba, Mason, Llano, Burnet, Gillespie, Blanco, Hays, Travis, Bastrop, Fayette |
| D. C. Draper | Fayette |

## GEOGRAPHY

The physiographic expression of the Colorado River basin ranges from high flat treeless plains, to rugged hills, to the broad coastal plains. Land-surface elevations in the basin range from sea level at the mouth of the Colorado River to about 4,000 feet at the New Mexico-Texas State line. The Texas Water Development Board has subdivided the Colorado River basin into smaller drainage areas for water-resources planning as shown on Plates 1, 2, and 3.

The climate of the Colorado River basin is characterized by hot summers and mild winters except for occasionally severe cold temperatures in the High Plains portion of the basin. Average annual precipitation ranges from less than 15 inches at the upper end of the basin to more than 40 inches near the coast. Conversely, average net lake-surface evaporation rates range from about 10 inches per year at the coast to about 70 inches per year in the northwestern part of the basin. The average monthly precipitation for the period of record at selected stations in the Colorado River basin is shown on Figure 3. Precipitation during spring and summer months generally is in the form of scattered thunderstorms; during fall and winter months it is more widespread and generally of longer duration.

The population of the Colorado River basin in 1960 was approximately 758,000, or nearly 8 percent of the State's total population. Within the basin, 73 percent of the people lived in urban areas (communities of 2,500 or more inhabitants). The remainder of the population is classified as rural. Twenty-eight cities with populations of 2,500 or more lie within or partly within the basin.

The economy of the basin is based primarily on varying forms of agriculture with oil and gas production scattered throughout the basin contributing heavily to the economy.

The geography of each of the three regions of the Colorado River basin, shown on Figure 1, is discussed at greater length in the following text.

## Region I

The surface topography over much of Region I is a gently sloping plain extending from the New Mexico-Texas State line to an eastward-facing escarpment in Borden, Dawson, and Howard Counties. This plains area is a part of the Southern High Plains. East of the escarpment the topography is characterized by low rolling hills, punctuated by prominent mesas. The altitude of the land surface in Region I ranges from about 2,000 feet along the Colorado River in Mitchell County to approximately 4,000 feet in Cochran County at the northwestern corner of the region.

Of the 12,280 square miles comprising Region I in the upper Colorado River basin in Texas, most of the Southern High Plains portion (approximately 6,400 square miles) contributes no runoff to the Colorado River. Drainage of the plains surface is very poorly developed, consisting of wide, shallow, and poorly defined valleys or draws. Surface water accumulating in these draws ordinarily flows for only a short distance before being lost by seepage and evapotranspiration. The eastern and extreme southern part of Region I is drained by the Colorado River and its tributaries. (See Plate 1.)

The 1931-55 average annual precipitation ranged from about 15 inches in the western part of Region I to about 20 inches in the eastern part. Figure 4 shows the annual precipitation at Seminole from 1923 to 1960, and at Big Spring from 1900 to 1960. About 70 percent of the annual precipitation falls during the period from April to October, or during the region's growing season. The average monthly distribution of precipitation for the periods of record at Seminole and Big Spring weather stations is shown on Figure 3. High-velocity winds and generally warm temperatures cause high evaporation rates in Region I. Average net lake-surface evaporation rates for the period 1940-57 ranged from about 60 inches per year in the southeastern part of the region to about 70 inches per year in the northwestern part.

Approximately 304,000 people, or 40 percent of the Colorado River basin's population in Texas, reside in Region I. Of these, 78 percent live in urban areas.

The economy of the region is based primarily on petroleum and agricultural industries. Row-crop farming is of prime importance in the region and includes a considerable amount of irrigation farming. The principal income crops, farmed by both dry-land and irrigation methods, are cotton and grain sorghums. In addition to farming, livestock raising also contributes to the agricultural economy. Oil and (or) gas is produced in all counties of Region I. In addition, oil-field service companies, natural gas plants, oil refineries, carbon black plants, sulphur extraction plants, petrochemical plants, and related industries contribute heavily to the region's economy.

## Region II

The diverse physiographic expressions in Region II range from low rolling hills, of the North Central Plains, in the north to high plateaus in the south. The altitude of the land surface ranges from about 700 feet at Lake Travis, in the southeastern part of the region, to about 2,900 feet in Upton County, in the northwestern part. The North Central Plains, which is encountered in the southeastern part of the Region I, continues into Region II, and occupies much of the area north and west from Brown and McCulloch Counties. In Region II, the North Central Plains consists of a bench topography covered with mesquite and prairie grasses. About 20 miles south of the Colorado River, the topography changes from that of the North Central Plains to the more rugged topography of the Edwards Plateau and the "hill country." The Edwards Plateau occupies the southwestern part of the Region II west and north from Gillespie County, and is generally flat and featureless on its highest parts except for occasional sinkholes formed by solution of the limestone bedrock. Where drainage has developed, streams have cut through the resistant limestone, forming canyons of considerable relief. The "hill country," situated east of the Edwards Plateau and southeast of the North Central Plains, occupies the southeastern part of Region II. The "hill country" is generally an area of steep hills with cedar-covered slopes, but its central part, sometimes called the "Central Mineral Region," is characterized by bald "granite" hills of moderate relief.

Region II embraces an area of approximately 24,550 square miles. Major tributaries of the Colorado River in the region are the Concho, San Saba, Llano, and Pedernales Rivers, and Pecan Bayou. The major tributaries and drainage subdivisions in Region II are shown on Plate 2.

The 1931-55 average annual precipitation ranged from about 15 inches in Upton County to about 32 inches in Travis County. Figure 4 shows the annual precipitation at the San Angelo station from 1908 to 1960 and at the Brady station from 1941 to 1960. The average monthly distribution of precipitation for the periods of record at the San Angelo and Brady stations is shown in Figure 3. Most of the annual precipitation in Region II occurs during the spring and summer months. Evaporation rates are generally high throughout most of Region II because of low humidity, generally strong winds, and hot summers. Average net lake-surface evaporation rates for the period 1940-57 ranged from about 40 inches per year in the southeastern part of the region to about 70 inches per year in the northwestern part.

Although Region II constitutes more than half the total land-surface area of the Colorado River basin, only about 25 percent of the basin's population, or about 193,000 inhabitants, reside in the region. Slightly more than 50 percent of the population lives in urban areas.

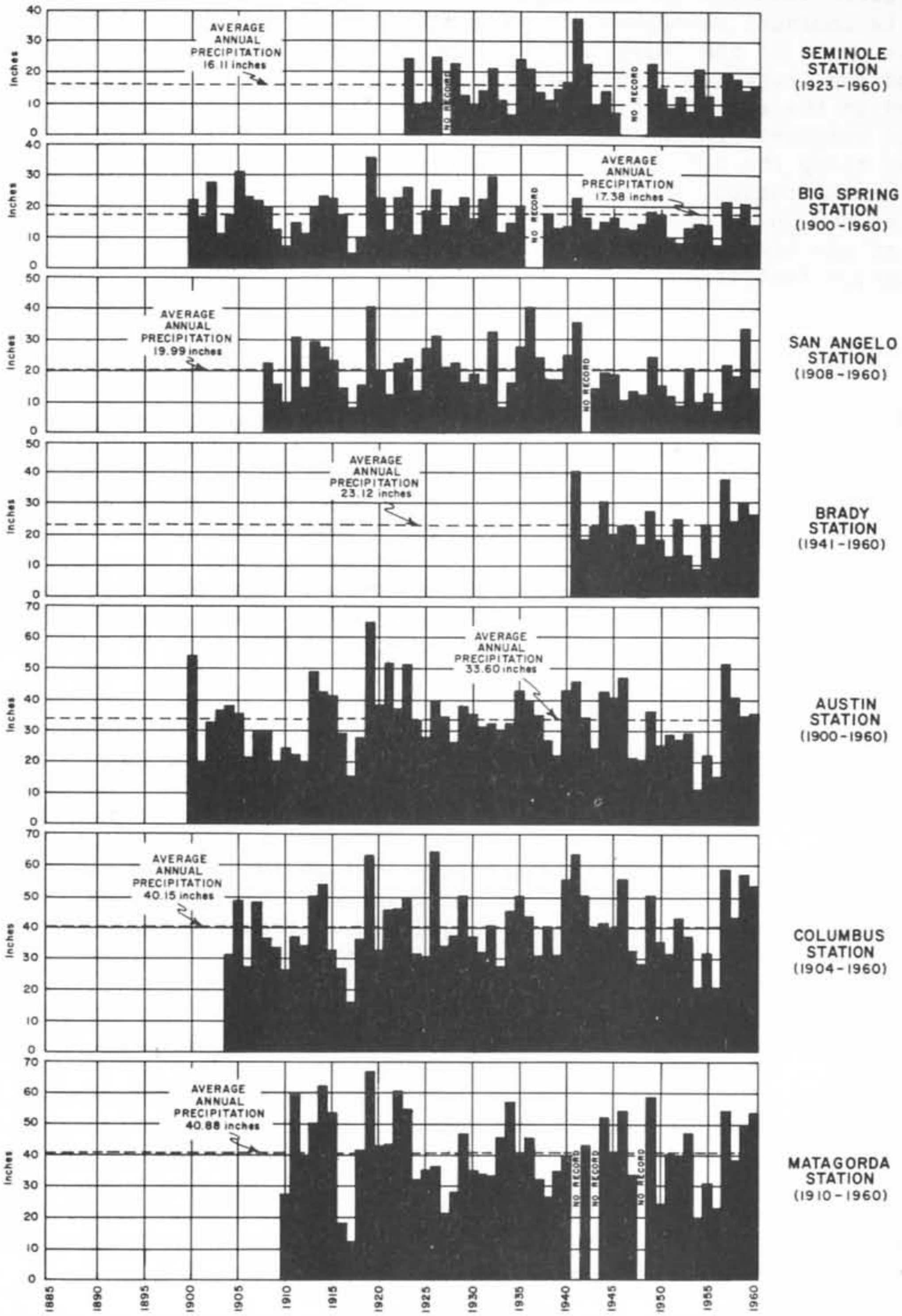



Figure 4

Annual Precipitation for Period of Record at Selected Stations in Colorado River Basin

(From U. S. Weather Bureau Data)

Texas Water Development Board in cooperation with the U. S. Geological Survey

The economic development of Region II is largely agricultural, although the petroleum industry is very important in the northwestern half. Cattle raising is dominant throughout the region except on the Edwards Plateau and in higher parts of the "hill country," where conditions are more favorable for sheep and goat ranching. Both dry-land and irrigation row-crop farming are practiced in the region, the principal crops being, as in Region I, cotton and grain sorghum. Peach orchards are common in the "hill country," and pecans are grown along the banks of perennial streams. Oil and gas is produced throughout the region, except in the "hill country" where the principal mineral industries are those of building stone and crushed rock. The "hill country," because of its scenic beauty and abundant wildlife, is economically developed in recreation facilities.

## Region III

The gentle topography of the coastal region covers most of Region III, except for the northwestern part, which is characterized by the steep cedar-covered slopes of the "hill country." The boundary between the "hill country" and the Gulf Coastal Plain is abrupt, and is marked by the southeast-facing scarp known as the Balcones Escarpment, which passes through Austin. The coastal region is moderately hilly to the northwest, where it is forested with pine and oak. Toward the coast the terrain becomes flat and features many poorly drained areas. The altitude of the land surface in Region III ranges from sea level in the southeastern part to about 1,600 feet in Hays County, the northwestern part.

Region III is quite narrow and embraces an area of 3,610 square miles. The region is drained by the Colorado River and its tributaries. The Colorado River and its tributaries within Region III are shown on Plate 3, along with the region's drainage subdivisions.

The average annual precipitation from 1931 to 1955 ranged from approximately 32 inches in Travis County to a little more than 40 inches in Matagorda County. Figure 4 shows the annual precipitation at Austin from 1900 to 1960, at Columbus from 1904 to 1960, and at Matagorda from 1910 to 1960. The distribution of rainfall throughout the year varies from place to place in the region. Graphs showing the average monthly precipitation for the periods of record at Austin, Columbus, and Matagorda stations are presented on Figure 3.

Average net lake-surface evaporation rates for the period 1940-57 ranged from about 10 inches per year at the coast to about 40 inches per year in the northwestern part of the region.

Region III has approximately 261,000 inhabitants, or about 35 percent of the Colorado River basin's population in Texas. About 80 percent of the region's population is in urban areas, principally Austin.

The economy of Region III except for metropolitan Austin is dependent upon agricultural and petroleum industries. Cattle production is dominant throughout the region. Cattle are raised almost entirely for beef production, although there are some dairy industries of local importance in the lower part of the region. Farming consists of both dry-land and irrigation methods, the principal crops harvested being rice, grain sorghums, and cotton. Rice production, which requires irrigation, is restricted to the low-lying coastal areas.

Oil and gas production and associated industries also contribute to the economy of Region III, primarily in the southern half. In addition, there are some light industries in the vicinity of Austin. Much of the economy of metropolitan Austin is associated with activities of State and Federal governmental agencies.

## GENERAL GEOLOGY

The present-day geology of the Colorado River basin reflects the various depositional phases and environments that have taken place through geologic time. Those depositional phases most directly related to ground water in the basin occurred during Cambrian, Ordovician, Pennsylvanian, Permian, Triassic, Cretaceous, Tertiary, and Quaternary Periods.

During late Cambrian time in Region II, a sequence of near-shore marine sand, shale, and limestone was deposited on a rugged surface of Precambrian metamorphic and igneous rocks. Toward the close of Cambrian time and during the Ordovician Period, thick sequences of limestone and dolomite were deposited.

Prior to the deposition of Pennsylvanian sediments, there was a period of emergence and subsequent erosion with perhaps only minor deposition of Devonian and Mississippian sediments in Region II. During Pennsylvanian time deposition of sediments in widespread seas produced a sequence of marine sand, shale, and limestone over a large part of the Colorado River basin. Rocks ranging in age from Precambrian to Pennsylvanian are exposed at the surface in the eastern one-third of Region II. Cambrian, Ordovician, and Pennsylvanian rocks dip in all directions away from a structural feature known as the Llano uplift, which is centered in Llano County. Also, during Pennsylvanian time thick sequences of shale and limestone were deposited in a sea which covered much of West Texas. This deposition was accompanied by regional subsidence. The area of subsidence and deposition is called the Permian basin and occurs throughout most of Region I and in the northwestern part of Region II.

During the Permian Period great thicknesses of sand, shale, limestone, anhydrite, and salt were deposited in the Permian basin, and thin-bedded limestone and shale were deposited on its eastern margin, which passes through the western part of Region II. Sediments of Permian age appear at the surface in the north-central part of Region II and dip northwest.

Following the Permian Period, the non-marine sand, shale, and gravel of upper Triassic age were deposited in the continually subsiding Permian basin. Rocks of Triassic age appear at the surface in the eastern part of Region I and dip toward the west. In the western part of Region I Triassic rocks occur in the subsurface and dip toward the east. The deposition of Triassic sediments was followed by another period of erosion prior to deposition of Cretaceous sediments.

During the Cretaceous Period, seas advancing from the south first deposited coarse sand, and later, limestone, shale, fine sand, and silt, on the eroded Triassic land surface. The Cretaceous seas covered most of Texas, including all of the area of the present-day Colorado River basin. During late Cretaceous time the seas receded to the south. Sediments of Cretaceous age appear at the surface through the central part of the Colorado River basin and dip generally to the southeast.

During the Tertiary and Quaternary Periods thick sequences of sand and clay were deposited in the upper and lower extremities of the Colorado River basin.

During late and perhaps since early Tertiary time, areas north and west of Austin were emergent. Streams flowing across these areas, by continually shifting their courses, laid down extensive and in many places very thick deposits of clastic materials. Because of erosion associated with the development of the Colorado River drainage system, these deposits are now chiefly confined to Region I.

## Stratigraphy

The fresh-water-bearing portion of the stratigraphic section in the Colorado River basin is composed of rocks ranging in age from Precambrian to Recent. Table 1 shows the geologic units from youngest to oldest, their approximate thicknesses, a brief description of their lithology, and a brief summary of their water-bearing characteristics. Plates 1, 2, and 3 show the outcrops of major geologic units listed in Table 1. Plate 4, a geologic section generally along the axis of the Colorado River basin, shows the stratigraphic position and attitude of these rocks in the subsurface.

## Structure

Cambrian, Ordovician, and Pennsylvanian rocks dip away from the Llano uplift, a structural dome, the center of which is in Llano County. Faults are common in the Llano uplift region, and vertical displacements greater than 2,000 feet are known. The faults are practically vertical, and occurred during the Pennsylvanian or subsequent pre-Cretaceous Periods; they do not transect overlying Cretaceous strata.

Permian rocks which yield usable water dip to the northwest, into the Permian basin.

Triassic sediments were laid down in a large depositional basin which is coincident with the Permian basin. The Triassic beds dip toward the center of the Permian basin from both its east and west flanks.

The base of the Ogallala Formation slopes to the southeast. No faults are known to influence the occurrence and movement of ground water in Region I.

Cretaceous sediments dip gently to the southeast in all three regions. In Region III the Cretaceous rocks are cut by faults in Travis and Bastrop Counties. The main faults occur in a zone passing through Austin, the Balcones fault zone, where the upthrown side of the faults is to the northwest.

The Tertiary and Quaternary sediments in Region III dip gently toward the Coast. Some of the Tertiary sediments are faulted along the Luling-Mexia fault zone which passes through southeastern Bastrop County. In this fault zone the upthrown side is to the southeast. In addition to the Luling-Mexia and Balcones fault zones, there are numerous small faults throughout the basin.

The geologic section along the axis of the Colorado River basin, Plate 4, illustrates the general structural features of the various rock units.

## Fresh-Water Aquifers

An aquifer is defined as a geologic formation, a group of formations, or a part of a formation that is water bearing, and use of the term is usually restricted to those water-bearing units that are capable of yielding water in quantities sufficient to constitute a usable supply. An impermeable formation, a geologic formation which, although porous and capable of absorbing water slowly, will not transmit it rapidly enough to furnish significant quantities for a well or spring, is called an aquiclude. Because of their varying abilities for supplying ground water, the aquifers of the State are classified on a statewide basis as major and minor water-bearing formations (Texas Board of Water Engineers, 1958, p. 33).

Aquifers that are important on a statewide basis may or may not be of equal importance as a source of ground water in any individual river basin. Their importance within a river basin depends largely on the amount of water they can supply in relation to the total amount of available ground water that can be developed in the basin. An aquifer that is important on a statewide basis may have, within a river basin, limited areal extent or unfavorable hydrogeologic characteristics that do not reflect its statewide importance. Therefore, for discussion in this report, the aquifers have been classified as primary or secondary according to their importance within the Colorado River basin.

A primary aquifer is defined as an aquifer that is capable of supplying large quantities of water over a large area of the basin. The two primary aquifers of the Colorado River basin are the (1) Ogallala and (2) Edwards-Trinity (Plateau).

A secondary aquifer is defined as an aquifer that is capable of supplying large quantities of water in small areas or relatively small quantities of water in large areas of the basin. The six secondary aquifers of the Colorado River basin are:

| | |
|---|---|
| Edwards-Trinity (High Plains) | Hickory |
| Santa Rosa | Carrizo-Wilcox |
| Ellenburger-San Saba | Gulf Coast |

In addition to the primary and secondary aquifers of the Colorado River basin, other aquifers yield small to moderate quantities of water locally. Although their potential is believed limited, they are currently supplying small quantities of water for municipal, industrial, irrigation, domestic, or livestock-watering purposes in local areas of the basin.

Figure 5 indicates the areal relationship of the primary and secondary aquifers of the Colorado River basin.

# GENERAL GROUND-WATER HYDROLOGY

This section has been included to acquaint the reader with the basic fundamentals of ground-water hydrology and to define the terms used in this report.

Table 1.--Geologic units and their water-bearing characteristics, Colorado River basin

| System | Series | Group | Stratigraphic unit | Approximate thickness (feet) | Character of rocks | Water-bearing characteristics |
|---|---|---|---|---|---|---|
| Quaternary | Pleistocene and Recent | | Dune sand and lake deposits | 0- 100+ | Fine sand and gypsiferous clay. | Not known to yield usable water in the basin. |
| | | | Alluvium | 0- 200 | Unconsolidated clay, silt, sand, and gravel. | Yields small amounts of water in isolated areas of stream valleys. |
| | Pleistocene | | Beaumont Clay | 0- 500+ | Varicolored calcareous clay and sand layers. | Yields large amounts of water in Region III. |
| | | | Lissie Formation | 0- 800 | Alternating layers of fine to coarse sand interbedded with sandy clay and clay. | Do. |
| Tertiary | Pliocene | | Ogallala Formation | 0- 300 | Varicolored clay, silt, and fine- to coarse-grained, gray to red sand; contains some quartz gravel and caliche. | Yields large amounts of water in Region I. |
| | | | Goliad Sand | 0- 250 | Sand interbedded with gravel and clay. | Yields large amounts of water in Region III. |
| | Miocene(?) | | Lagarto Clay | 0- 400 | Varicolored clay with interbedded sand. | Yields small to moderate amounts of water in Region III. |
| | Miocene | | Oakville Sandstone | 0- 200 | Quartz or calcitic sand, often cross bedded; minor clay beds. | Yields large amounts of water in Region III. |
| | Miocene(?) | | Catahoula Sandstone | 0- 200 | Bentonitic clay and volcanic ash with minor sand layers. | Yields small amounts of water in Region III. |
| | | | Igneous intrusives | | Basalt. | Not known to yield usable water in the basin. |
| | Oligocene | | Frio Formation | 0-1,200 | Alternating beds of sand and clay. | Do. |
| | | | Vicksburg Formation | 0- 500 | do | Do. |
| | Eocene | Jackson | | 0-1,400 | Sand, clay, lignite, significant intermittent beds of bentonite, bentonitic clay, and volcanic ash. | Yields small to moderate amounts of water in Region III. |
| | | Claiborne | Yegua Formation | 0- 850 | Lignitic sand and sandy clay with minor amounts of bentonitic clay. | Do. |
| | | | Cook Mountain Formation | 0- 400 | Blue glauconitic clay with thin layers of argillaceous calcareous sand. | Not known to yield usable water in the basin. |
| | | | Sparta Formation | 0- 200 | Ferruginous glauconitic sand with clay layers in upper portion. Pinches out toward coast. | Yields highly mineralized water except in areas of outcrop. |
| | | | Mount Selman: Weches Formation | 0- 75 | Glauconitic calcareous silty clay. | Not known to yield usable water in the basin. |
| | | | Mount Selman: Queen City Formation | 0- 500 | Well sorted sand, glauconitic in part, with beds of bentonitic clay. | Yields moderate amounts of water in Region III. |
| | | | Mount Selman: Reklaw Formation | 0- 300 | Ferruginous glauconitic fine-grained sand and clay; basal sands grade upward into clay. | Basal portion, where not hydraulically connected to Carrizo sand, yields moderate amounts of mineralized water. |

(Continued on next page)

## Hydrologic Cycle

The hydrologic cycle is the sum total of processes and movements of the earth's moisture from the sea through the atmosphere to the land, and eventually, with numerable delays en route, back to the sea. Figure 6 illustrates a number of the courses which the water may take in completing the cycle. All water occurring in the Colorado River basin, whether surface water or ground water, is derived from precipitation.

## Occurrence and General Hydraulics

Ground water is contained in the interstices or voids of pervious strata. Two rock characteristics of fundamental importance in the occurrence of ground water are porosity, or the amount of open space contained in the rock, and permeability, which is the ability of the porous material to transmit water. Fine-grained sediments, such as clay and silt, commonly have high porosity; but due to the small size of their voids, they do not readily yield or transmit water. Therefore, in order for a formation to be an aquifer it must be porous, permeable, and water-bearing. The term "sands" as used in this report refers to distinct layers or beds or sand through which water is most readily transmitted.

Precipitation on the outcrop of an aquifer may take one of many courses in completing the hydrologic cycle. A large percentage of it is evaporated back to the atmosphere directly or is consumed by plants and returned to the atmosphere by transpiration. Some of the water will run off the land surface into streams and thus return to the sea. A small percentage of the rainfall will percolate downward under the force of gravity to a zone in which all rock voids are saturated. This zone is known as the zone of saturation; its upper surface, the water table. Water entering the zone of saturation moves to points of lower elevation where it is discharged naturally or artificially and subjected to other phases of the hydrologic cycle. Occasionally a local impermeable layer above the water table will intercept the downward percolation of the water, creating a saturated zone above the main water table. This zone, usually of small areal extent, is known as a perched water table.

Water in an aquifer may occur under water-table or artesian conditions. In the outcrop area of an aquifer, ground water generally occurs under water-table conditions, that is, the water surface is unconfined and at atmospheric pressure. The hydraulic gradient in an unconfined aquifer is the slope of the water table. Downdip from the outcrop or recharge area, ground water occurs under artesian conditions where the water in a dipping permeable stratum is confined between relatively impermeable beds. The water is then under sufficient pressure to rise above the top of the confining bed when the water-bearing stratum is penetrated by a well. Pressure head is expressed as the height of a column of water that can be supported by the pressure. The level to which water will rise in wells completed in an artesian aquifer is called the piezometric surface. The loss of water from an artesian aquifer by natural discharge causes a loss in pressure resulting in lower elevations of the piezometric surface in the direction of water movement. The hydraulic gradient in an artesian aquifer is determined by the slope of the peizometric surface.

The water-producing capability of an aquifer depends upon its ability to store and to transmit water. Although the porosity of a rock is a measure of

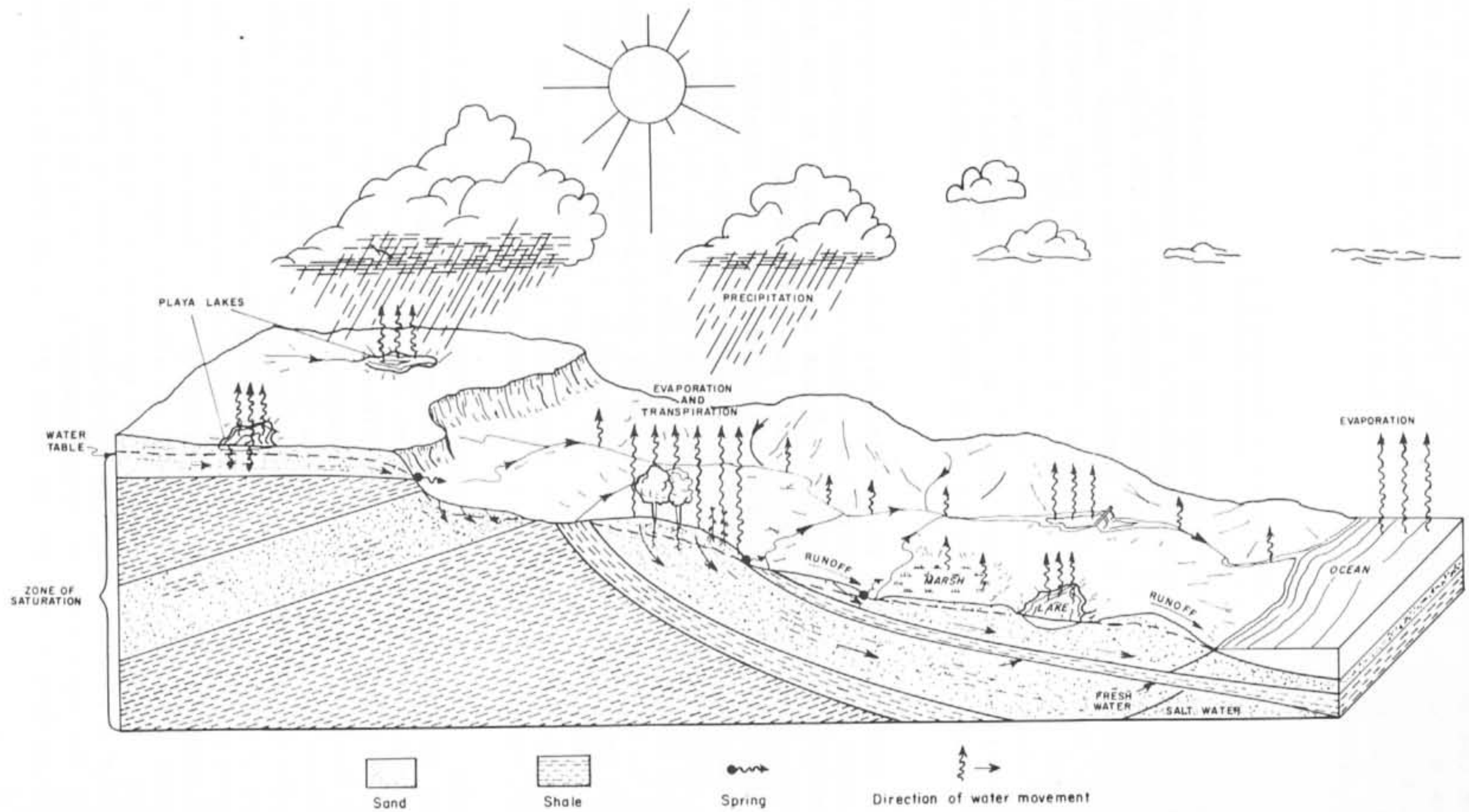



Figure 6

## Idealized Hydrologic Cycle, Colorado River Basin

Texas Water Development Board in cooperation with the U.S. Geological Survey its capacity to store water, not all of this stored water can be recovered by pumping. Some of the water stored in the interstices is retained because of the surface tension of water and molecular attraction of the rock particles for water. The coefficient of storage is equal to the amount of water in cubic feet that will be released from or taken into storage by a vertical column of the aquifer having a base 1 foot square when the water level or hydrostatic pressure is lowered or raised 1 foot. In a water-table aquifer, the storage coefficient is essentially equal to the specific yield, which is the ratio of the volume of water a saturated material will yield under the force of gravity to the total volume of material drained. In an artesian aquifer, ground water is withdrawn from storage without dewatering the aquifer. As water is removed from the artesian aquifer the hydrostatic pressure is lowered. The weight of the overlying sediments, which were partially supported by the hydrostatic pressure, compresses the water-bearing material, causing some water to be released from storage. Thus, a portion of the volume of water taken from an artesian aquifer can be attributed to expansion of the water so produced.

The quantity of water an aquifer receives as recharge and the ability of the aquifer to transmit water to the areas of discharge are two principal factors that must be considered in determining the amount of water available for sustained withdrawal. The coefficient of transmissibility is an index of an aquifer's ability to transmit water. It is defined as the amount of water in gallons per day that will pass through a vertical strip of the aquifer 1 foot wide under a hydraulic gradient of 1 foot per foot. By using the coefficient of transmissibility, the amount of water that will pass through an aquifer under various hydraulic gradients can be determined. The coefficient of permeability is defined as the quantity of water in gallons per day that will pass through a section of the aquifer 1 foot square under a hydraulic gradient of 1 foot per foot. This parameter can be determined by dividing the coefficient of transmissibility by the saturated thickness of the aquifer in feet.

Coefficients of storage and of transmissibility are determined from pumping tests of wells that screen a water-bearing formation. The term "screen" is used to define the zones in a well's casing that are open to the aquifer, either by means of well screens or by other similar openings, in order to permit water to enter the well bore. A pumping test consists of pumping water from a well at a constant rate for a period of time while making periodic measurements of water levels in the pumping well and, if possible, in one or more observation wells. The recovery of the water level is also measured after pumping stops. From the data obtained the coefficients of transmissibility and storage can be calculated by means of certain formulas. In general, the storage coefficient can be determined only if data are obtained from at least one observation well. The coefficients of transmissibility and storage can be used in computing the effects that pumping water from a well will have on water levels in the aquifer at various times and at various distances from the pumped well. These coefficients also can be used in computing the quantity of water that will flow through a given section of the aquifer and in estimating the availability of water from storage. A general indicator of an aquifer's hydraulic characteristics is provided by the specific capacity of a well. This specific capacity is defined as the gallons per minute a well will produce for each foot of water-level drawdown that has occurred at the end of a period of time during which the well has been pumped at a constant pumping rate. However, the type of well construction and the efficiency of well development also have an effect on the well's specific capacity that is not directly related to the aquifer's hydraulic characteristics.

## Recharge, Discharge, and Movement

Recharge is the addition of water to an aquifer that results in an aggregation in storage. The principal source of ground-water recharge in the Colorado River basin is precipitation which falls on the outcrop of the various aquifers. In addition, seepage from streams and lakes located on outcrop areas and possibly interformational leakage are sources of ground-water recharge. In parts of Region I, water from playa lakes is being artificially injected into the aquifer through recharge wells. Recharge is a limiting factor in the amount of water that can be developed perennially from an aquifer, as it must balance discharge over a long period of time or the water in storage in the aquifer will eventually be depleted. Among the factors influencing the amount of recharge received by an aquifer are: the amount and frequency of precipitation; the areal extent of the outcrop or intake area; the topography, type and amount of vegetation, and condition of the soil cover on the outcrop; and the ability of the aquifer to accept recharge and transmit it to areas of discharge.

Discharge is the loss, or withdrawal, or ground water from an aquifer by either natural or artificial means. Natural discharge includes effluent seepage, spring flow, evaporation from free water surfaces, transpiration of plants, and interformational leakage. Artificial discharge takes the form of discharge from flowing and pumped water wells, from drainage ditches, from gravel pits, and from other artificially induced excavations that intersect the water table.

Ground water moves from areas of recharge to areas of discharge or from points of higher hydraulic head to points of lower hydraulic head. Ground-water movement, like surface-water flow, is in the direction of the hydraulic gradient. Under water-table conditions, the slope of the water table and consequently the direction of ground-water movement is often closely related to the slope of the land surface. Under normal artesian conditions, movement of ground water usually is in the direction of the aquifer's regional dip. However, in the case of both artesian and water-table conditions, local flow anomalies are developed in areas of pumping and some water moves toward the point of artificial discharge. The rate of ground-water movement in an aquifer is usually very slow, being in the magnitude of a few feet to several hundred feet per year, except in cavernous limestones where the rate of movement is often much greater.

## Fluctuations of Water Levels

Changes in water levels in an aquifer are due to many causes. Some are of regional significance whereas others are extremely local. The more significant causes of water-level fluctuations are changes in recharge and discharge. When recharge is reduced, as during periods of drought, some of the water discharged from the aquifer must be withdrawn from storage and water levels decline. However, when adequate rainfall resumes, the volume of water drained from storage in the aquifer during the drought may be replaced and water levels will rise accordingly.

When water is pumped or allowed to flow from a well, water levels in the vicinity are drawn down in the shape of an inverted cone with its apex at the discharging well. The development or growth of this cone depends on the aquifer's coefficients of transmissibility and storage, and on the well's rate of discharge. As withdrawal continues the cone expands and continues to do so until it intercepts a source of replenishment capable of supplying sufficient water to satisfy the withdrawal demand. This source of replenishment can be either intercepted natural discharge or induced recharge. If the quantity of water received from these sources is sufficient to compensate for the quantity of water being withdrawn, the growth of the cone will cease and new balances between recharge and discharge are achieved. In areas where recharge or salvagable natural discharge is less than the amount of water being withdrawn from wells, water is removed from storage in the aquifer to supply the deficiency and water levels will continue to decline.

Where intensive development has taken place in ground-water reservoirs, the individual well cones of depression sometimes coalesce, resulting in the development of a regional cone of depression. When the cone of one well overlaps that of another, interference occurs and an additional lowering of water levels occurs as the wells compete for water by expanding their cones of depression. The amount or extent of interference between cones of depression depends on the rate of withdrawal from each well, the spacing between the wells, and the hydraulic characteristics of the aquifer in which the wells are completed.

Water levels in some wells, especially those completed in artesian aquifers, have been known to fluctuate in response to such phenomena as changes in barometric pressure, tidal force, and earthquakes. However, the magnitude of the fluctuations are usually very small.

## GENERAL CHEMICAL QUALITY OF GROUND WATER

All ground water contains dissolved minerals, the character and concentration of which depend on the environment, movement, and source of the ground water. Water, in its role of the most universal solvent known to man, dissolves mineral matter from the soil and the component rocks of an aquifer. The quantity of mineral matter that is dissolved depends on the solubility of the minerals present in the rocks, the length of time the water is in contact with the rocks, the temperature of the water, and the amount of dissolved carbon dioxide contained in the water. With increasing depth the concentrations of dissolved minerals in the water, as well as the temperature of the water, generally increase. Greater concentrations also occur in stratigraphic units where ground-water circulation is restricted. In most stratigraphic units whose sediments were deposited in brackish water, the flushing action of fresh water moving through the aquifer has not been complete throughout the strata. Therefore, at some distance downdip and in some cases in limited areas, highly mineralized water is encountered.

The term "fresh water" commonly varies in meaning according to the quantity of usable-quality water that is available in an area. For discussion purposes in this report, unless otherwise noted, the terms "fresh" and "usable" refer to water containing dissolved-solids concentrations of less than 3,000 ppm (parts per million).

In addition to natural mineralization of water, the quality of water also can be impaired (contaminated) by man. Contamination can occur from the disposal of industrial waste into improperly completed or faulty disposal pits and disposal wells. Inadequate plugging of test holes and severe corrosion of well casing permit highly mineralized water to enter and contaminate fresh-water aquifers. The quality of water in an individual water well can be affected by the well's construction through improper casing or cementing, which allows water of poor quality to enter the well or move into a fresh-water aquifer having a lower hydrostatic head. Contamination also can occur through the improper disposal of wastes either into the ground or into surface streams which may provide recharge to ground-water aquifers.

The chemical quality of uncontaminated ground water, unlike that of surface water, remains relatively constant at all times. This in addition to its constant year-round temperature makes ground-water supplies highly desirable for many uses.

## Standards

The principal mineral constituents found in ground water are calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, silica, iron, manganese, nitrate, fluoride, and boron. Water used for municipal supplies should be colorless, odorless, palatable, and where possible should meet the standards set by the U.S. Public Health Service (1962, p. 2152-2155) for drinking water used on interstate carriers. Some of these standards are as follows:

| Substance | Concentration (ppm) |
|---|---|
| Chloride (Cl) | 250 |
| Fluoride (F) | (*) |
| Iron (Fe) | 0.3 |
| Manganese (Mn) | 0.05 |
| Nitrate ($NO_3$) | 45 |
| Sulfate ($SO_4$) | 250 |
| Total 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.

| Annual average of maximum daily air temperatures (°F) | Recommended control limits of fluoride concentrations (ppm) | | |
|---|---|---|---|
| | Lower | Optimum | Upper |
| 50.0 - 53.7 | 0.9 | 1.2 | 1.7 |
| 53.8 - 58.3 | .8 | 1.1 | 1.5 |
| 58.4 - 63.8 | .8 | 1.0 | 1.3 |
| 63.9 - 70.6 | .7 | .9 | 1.2 |
| 70.7 - 79.2 | .7 | .8 | 1.0 |
| 79.3 - 90.5 | .6 | .7 | .8 |

Although the above standards are deemed desirable for municipal use, it must be recognized that many municipal supplies which cannot meet these standards must be used for the lack of a more suitable supply. Many supplies failing to meet all these standards have been in use for long periods of time without any apparent ill effects on the user.

Maxcy (1950, p. 271) states that water having a nitrate content in excess of 45 ppm should be regarded as unsafe for infant feeding. The presence of large quantities of nitrate may indicate contamination. Water containing more than 0.3 ppm iron and manganese combined is likely to cause objectionable staining of laundered clothes and plumbing fixtures.

Hardness of water is an important factor in domestic, municipal, and industrial supplies. The principal constituents causing hardness of water are calcium and magnesium. Water hardness is expressed in parts per million as calcium carbonate. An increase in hardness causes an increase of soap consumption in washing and laundering processes, and the formation of scale in boilers and other equipment. A generalized classification for hardness, which is commonly accepted as standard and useful as an index to the analyses of water, is as follows:

| Hardness range (ppm) | Classification |
|---|---|
| 0 to 60 | Soft |
| 61 to 120 | Moderately hard |
| 121 to 180 | Hard |
| 180+ | Very hard |

The tolerance in chemical quality of water for industrial use differs widely for different industries and different processes. One of the major items of concern to most industries is the development of water supplies which do not contain corrosive or scale-forming constituents that affect the efficiency of their boilers and cooling systems. Hardness and excessive amounts of silica and iron cause scale deposits which clog lines and reduce efficiency of heat exchange apparatus. Suggested water-quality tolerances for a number of industries are summarized by Moore (1940, p. 271) and by Hem (1959, p. 253).

Numerous factors are involved in determining the suitability of water for irrigation purposes. The type of soil, adequacy of drainage, types of crops, conditions of climate, and the quantity of water used--all have an important bearing on the continued productivity of irrigated acreages. According to a report by the U.S. Salinity Laboratory Staff (1954, p. 69), the characteristics that are important in determining a water's suitability for irrigation are: (1) total concentration of soluble salts, expressed in terms of specific conductance; (2) the relative proportion of sodium to the other principal cations (magnesium, calcium, and potassium), expressed as percent sodium or sodium-adsorption ratio (SAR); (3) residual sodium carbonate (equivalents per million of carbonate in excess of calcium and magnesium); and (4) concentrations of boron or other elements that may be toxic. The report also includes a method for classifying irrigation waters.

## Treatment

Many waters of substandard quality can be made usable by various treatment methods. These methods include diluting (blending of poor and good quality waters to achieve an acceptable quality), softening, aerating, filtering, cooling, and adding various chemical additives. The limiting factor in water treatment is economy. Treatment processes for ground water usually do not have to be designed to handle large variations in quality.

# OCCURRENCE AND AVAILABILITY OF GROUND WATER

The magnitude of the review of ground-water conditions within the Colorado River basin necessitated the division of the basin from northwest to southeast along its longitudinal axis into Regions I, II, and III (Figure 1). Within each of the respective regions in the following discussions of the occurrence and availability of ground water, the aquifers are discussed in the order of their importance within the basin, as follows: (1) primary aquifers, (2) secondary aquifers, and (3) other aquifers of limited significance, which are treated briefly at the end of each regional discussion. The areal extent of each of the primary and secondary aquifers is shown on Figure 5.

## Region I

In Region I of the Colorado River basin are two primary aquifers, the Ogallala and the Edwards-Trinity (Plateau), and two secondary aquifers, the Edwards-Trinity (High Plains) and the Santa Rosa (Figure 5). It can be seen on Figure 5 that the Edwards-Trinity (Plateau) primary aquifer extends into Region II, where it covers a much larger area than in Region I; therefore, that portion of the aquifer occurring in Region I will be treated in this section of this report and the portion occurring in Region II will be discussed at length in that section. Also extending into Region II is a small portion of the Santa Rosa secondary aquifer; however, this small portion of the aquifer in southeastern Mitchell and southwestern Nolan Counties is included in this Region I discussion.

Other aquifers in Region I, those which are more limited in areal extent but which supply small to moderate quantities of ground water locally for municipal, industrial, irrigation, domestic, or livestock-watering purposes, are: the Chinle Formation, Cretaceous rocks (outliers), and alluvium.

### Primary Aquifers

#### Ogallala Aquifer

The Ogallala aquifer covers about 7,500 square miles of Region I of the Colorado River basin. The Ogallala's western boundary in Texas is arbitrarily selected at the Texas-New Mexico State line. To the north the Ogallala aquifer extends into the Brazos River basin. The selected southern boundary of the Ogallala aquifer in Andrews, Ector, Midland, and Glasscock Counties is based on thinning out of the saturated interval. In many places the Ogallala Formation occurs south and east of the aquifer considered in this report; however, in these places there is either little or no saturated thickness in the aquifer or the Ogallala Formation occurs as small outliers. The Ogallala aquifer, as considered in this report, constitutes the lower, saturated portion of the Ogallala Formation, but in some parts of the southern half of the aquifer's Region I occurrence, saturated Cretaceous sediments are included within the Ogallala aquifer. This inclusion of the Cretaceous deposits is in areas where they are not easily differentiated from Ogallala deposits or where small bodies of Cretaceous strata occur separately and distinctly from the main body of Cretaceous strata in Region I. Saturated alluvial deposits of Quaternary age are also included within the Ogallala aquifer. The extent of the Ogallala aquifer in Region I of the Colorado River basin is shown on Plates 5 and 6 and also on Figure 5.

### Geologic Characteristics

The Ogallala Formation rests unconformably on Triassic and Cretaceous rocks, and is composed of alternating beds of clay, caliche, and unconsolidated and mostly poorly-sorted gravel and sand. Caliche zones generally occur above the water table. Relative amounts of sand and gravel vary considerably from place to place.

Barnes and others (1949, p. 12), from consideration of 537 drillers' logs of wells penetrating the Ogallala Formation in Deaf Smith, Hale, Floyd, Swisher, and Lubbock Counties, concluded that 68 percent of the saturated interval, between 72 and 350 feet below land surface, was sand. Saturated thickness of the Ogallala is generally less than 100 feet in Region I, but varies widely from 0 to more than 150 feet in isolated areas.

The Ogallala's saturated thickness is largely controlled by the configuration of its base; thicker saturated intervals occur in ancient buried stream channels cut into the pre-Ogallala surface. The larger clastics and probably the greater permeabilities are governed by these channel deposits. Plate 6 indicates the distribution of saturation in the Ogallala aquifer in Region I.

As shown by the contours on Plate 5, the altitude of the base of the Ogallala aquifer generally ranges from about 2,400 feet above mean sea level in Howard County to about 3,700 feet in Cochran County. The general slope of the base of the Ogallala is approximately 11 feet per mile to the southeast, but because the base of these deposits is an ancient eroded land surface, slopes vary considerably over short distances.

### Occurrence and Movement of Ground Water

Ground water in the Ogallala aquifer generally occurs under water-table conditions, but locally artesian conditions are created by impermeable confining layers. Movement of water is generally in a southeasterly direction. The rate of movement varies throughout the aquifer, depending on the configuration of the base of the aquifer and permeability and saturation thickness. The regional water-level gradient is approximately 10 feet per mile to the southeast.

### Recharge and Discharge

The Ogallala aquifer in Region I receives recharge from precipitation on the land surface and from underflow from the corresponding part of the aquifer in New Mexico. The amount of water moving into Region I from New Mexico was calculated to be about 40,000 acre-feet per year. The calculations were based on present hydraulic gradients and saturated thicknesses along the State line and a coefficient of permeability of 400 gpd (gallons per day) per square foot.

An average value of coefficient of permeability of 400 gpd per square foot is generally accepted for the Ogallala throughout the Southern High Plains by the High Plains Underground Water Conservation District Number 1. The amount of underflow into Texas was related to the contributing area of Ogallala in

New Mexico in order to determine the annual estimated recharge from precipitation, which was 0.21 inches per year.

Assuming that 0.21 inches of the yearly precipitation recharges the Ogallala in Region I of the Colorado River basin, approximately 80,000 acre-feet of recharge would be received by the aquifer annually in this region. Hence, total recharge may be on the order of 120,000 acre-feet per year. However, this amount of recharge is assumed to be evenly distributed over 4 1/2-million acres and is therefore insignificant in application to major development.

Water is discharged from the Ogallala aquifer both naturally and artificially. Natural discharge occurs by evaporation and transpiration where the water table is close to the land surface, in areas of draws and alkaline lakes. Examples of evapotranspiration discharge areas are Cedar, McKenzie, and Shafter Lakes; water-table lakes and near-surface saturated deposits in southwestern Lynn and northwestern Dawson Counties; the Lost Draw complex in Terry and Dawson Counties; in Sulphur Springs Creek in Martin County; and small springs and seeps at the escarpment in Borden and Dawson Counties. The most significant discharge from the Ogallala is artificial, from the more than 6,000 irrigation, municipal, and industrial wells that pumped ground water from this aquifer in 1960.

## Water Levels

Depths to water range from the land surface along some draws to as much as 250 feet below the land surface in Cochran County.

The approximate depth at which water occurs below the land surface in the Ogallala aquifer is shown on Plate 7. Except in the northernmost part of Region I, the depth to water is less than 150 feet below the land surface. It is emphasized that Plate 7 presents only the approximate depth to water under static conditions, and depths to water under pumping conditions cannot be obtained from the information shown.

Annual fluctuations of water levels within wells penetrating the Ogallala aquifer are related to changes in storage. Declines in water levels are related to withdrawal of ground water from storage. Hydrographs showing fluctuation of water levels in selected wells are present on Figure 7. Well 27-01-601 is in an industrial well field in northwestern Gaines County. Water levels in this well from 1949 through December 1961 indicate a net decline of about 15 feet. Well 28-49-803 is in an extensively developed area producing from channel-fill deposits beneath Mustang Draw in Martin County. Water levels in this area, reportedly near land surface in 1938, declined to approximately 130 feet in 1961. Well 27-19-601 is located southeast of Seminole in Gaines County, near Seminole Draw and remote from heavily pumped areas. Measurements for this well indicate a net water-level decline of only 3 feet from 1938 to 1960.

The average static water level in the city of Midland's well field northwest of Midland declined about 30 feet from 1953 to 1960, and in the city of Midland's well field in northwestern Martin County water levels in one well ranged from 91 feet in December 1959 to 98 feet in December 1961, showing a net decline of about 7 feet during the 2-year period. Records of water-level measurements made in 21 selected observation wells in Martin County indicate an average decline of more than 40 feet within a 15-year period ending in 1960.

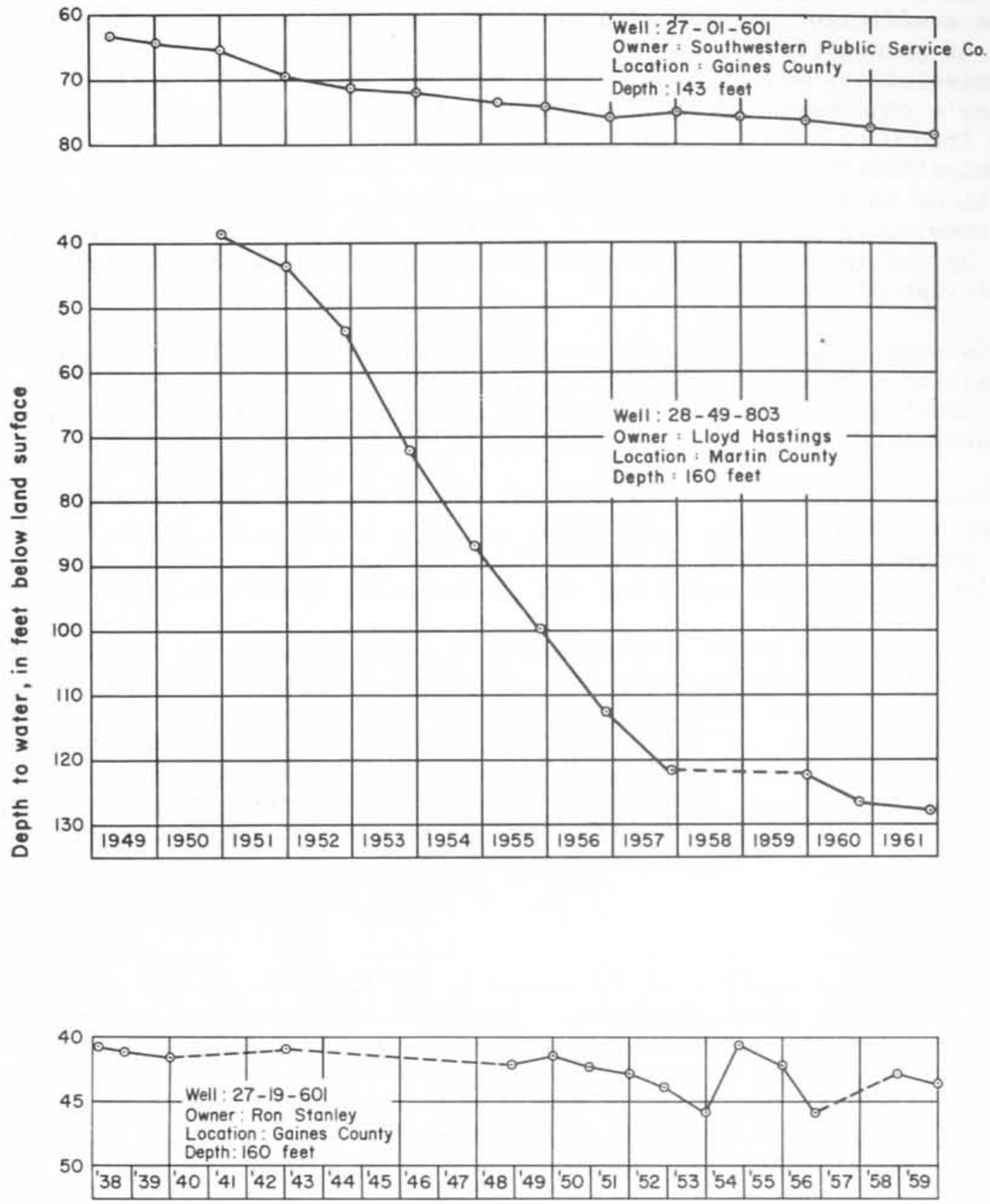



Figure 7

Hydrographs of Wells in the Ogallala Aquifer, Region I, Colorado River Basin

Texas Water Development Board in cooperation with the U. S. Geological Survey

### Water-Bearing Characteristics

The two most important properties of a water-table aquifer are its ability to store and to transmit water. These two properties are commonly designated as the coefficient of transmissibility (or a comparable property, the coefficient of permeability), and specific yield. The units for the coefficient of transmissibility are gallons per day per foot and include consideration of the aquifer's thickness. Because saturated intervals within the Ogallala aquifer range from 0 to more than 150 feet, it is evident that the coefficients of transmissibility may vary widely throughout the aquifer. Because of the wide variations in the Ogallala's saturated thickness, the approximate coefficient of transmissibility for any one locality is, for all practical purposes, determined by multiplying the saturated thickness of the aquifer by the average coefficient of permeability.

Consulting ground-water hydrologists, as a result of the statistical analysis of numerous pumping tests, have determined that the average coefficient of permeability for the Ogallala aquifer throughout the Southern High Plains is approximately 400 gpd per square foot.1/

Cronin (1961, p. 46) has indicated that the specific yield of the Ogallala aquifer is approximately 0.15. This specific yield value applies to the complete saturated interval of the aquifer, making no distinction between the non-contributing clays or silts and the contributing sands and gravels.

Figure 8 is a graph showing expected declines in water levels, at various distances from a pumping well, as a result of pumping at various rates for 30 days. The graph has been prepared using a coefficient of transmissibility of 50,000 gpd per foot and a specific yield of 0.15. This assumed transmissibility of 50,000 gpd per foot could apply to about a 125-foot saturated interval in the Ogallala aquifer. The graph indicates the desirability of proper well spacing in order to minimize mutual interference between pumping wells.

### Chemical Quality

The chemical quality of the water in the Ogallala aquifer varies widely within relatively short distances. Dissolved solids range from several hundred to several thousand parts per million. In general, the water of better quality occurs in those areas of the aquifer where the depth to water is greatest. The water is generally hard, and in almost all cases its fluoride content exceeds the limit recommended by the U.S. Public Health Service (1962, p. 2152-2155) for municipal supplies.

The locations from which about 200 water samples were collected, and the dissolved solids of the samples, are shown on Plate 5. The analyses presented were selected from more than 1,800 water analyses distributed throughout the study area. Table 2 presents the chemical analyses of 51 water samples selected from a more extensive list.

Variation in chemical quality of water in the Ogallala are both natural and man-made, but of primary concern are the cases in which dissolved solids are so great that the water is unfit for most beneficial uses.

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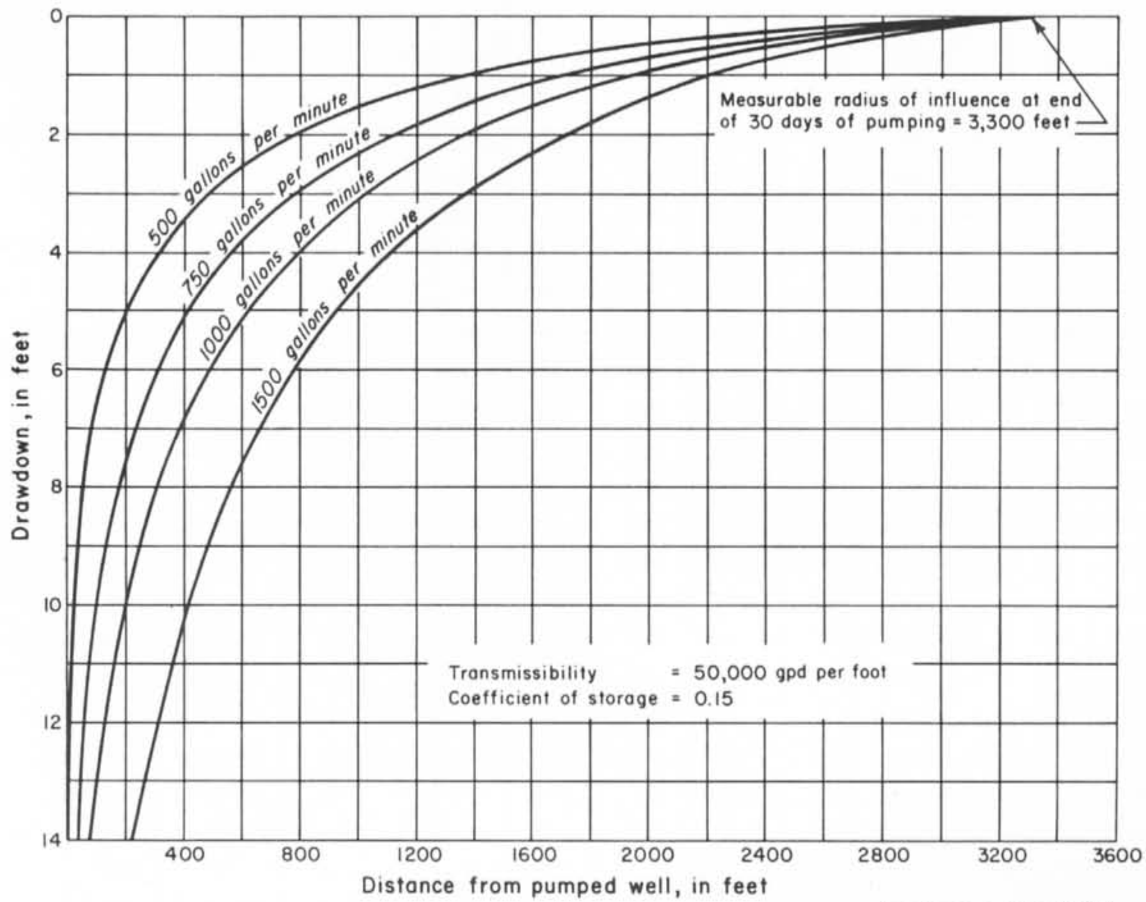
1/ Unpublished material, High Plains Underground Water Conservation District No. 1.




From Barnes and others (1949)

Figure 8

Distance-Drawdown Curves for a Well Completed Through the Ogallala Aquifer, After Pumping Continuously for 30 Days at Rates Indicated, Region I, Colorado River Basin

Texas Water Development Board in cooperation with the U. S. Geological Survey

Table 2.--Representative chemical analyses of water from primary and secondary aquifers, Region I, Colorado River basin

(Analyses expressed in parts per million except specific conductance and pH.)

| Well | Owner | Depth to well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Ogallala Aquifer | | | | | | | | | |
| 24-17-5 | J. C. Obrien | 180 | 5-24-61 | 57 | -- | 80 | 49 | 55 | 200 | 211 | 90 | 1.9 | 4.8 | 745 | 401 | 977 | 7.3 |
| 33-7 | Roe Bavosette | 210+ | do | 46 | -- | 76 | 35 | 58 | 192 | 183 | 74 | 1.8 | 2.0 | 615 | 334 | 875 | 7.2 |
| 34-9 | Phillips Petroleum Co. | 204 | 5-25-61 | 59 | -- | 64 | 38 | 49 | 254 | 83 | 82 | 3.0 | 4.5 | 558 | 316 | 820 | 7.3 |
| 35-2 | Charles Cathey | 210 | 8-10-61 | 43 | -- | 195 | 178 | 149 | 220 | 152 | 852 | -- | 2.8 | 1,680 | 1,220 | 3,060 | 7.1 |
| 2 | Tarves Devel. Co. | 210 | 7-21-60 | 45 | -- | 52 | 64 | 51 | 236 | 178 | 80 | 3.4 | 1.8 | 637 | 392 | 933 | 7.3 |
| 37-4 | Texaco, Inc. | -- | 8-10-61 | 43 | -- | 410 | 278 | 1,110 | 253 | 134 | 3,000 | -- | -- | 5,100 | 2,170 | 9,020 | 7.0 |
| 8 | A. A. Slaughter | 140 | 7-28-39 | -- | -- | 62 | 50 | 58 | 354 | 101 | 66 | -- | -- | 511 | 361 | -- | -- |
| 47-2 | City of Meadow | 140 | 4- -50 | 57 | 0.17 | 45 | 78 | 123 | -- | 185 | 131 | 4 | 10 | 833 | 433 | -- | 7.5 |
| 4 | Katherin Kennedy | 74 | 6- 6-38 | -- | -- | 65 | 96 | 314 | 439 | 531 | 218 | 5.2 | .09 | 1,451 | 555 | -- | -- |
| 8 | McDonald | 80 | 5-18-38 | -- | -- | 246 | 416 | 2,467 | 403 | 4,570 | 1,830 | 6.4 | -- | 9,733 | 2,326 | -- | -- |
| 50-5 | D. B. McGinty | 128 | 11-30-44 | -- | -- | 114 | 111 | 213 | 241 | 779 | 102 | 5.5 | 8 | 1,490 | 741 | -- | -- |
| 52-5 | D. E. Green | 120 | 6-20-44 | -- | -- | 70 | 101 | 198 | 287 | 301 | 320 | -- | 24 | 1,160 | 590 | -- | -- |
| 61-8 | W. M. Green | 142 | 5-23-44 | -- | -- | 75 | 95 | 186 | 288 | 373 | 254 | -- | -- | 1,120 | 578 | -- | -- |
| 63-3 | W. V. Fenter | 104 | 10- -46 | -- | -- | 60 | 82 | 124 | 421 | 222 | 128 | -- | .05 | 932 | 486 | -- | -- |
| 3 | R. J. Purtel | 38 | 6-14-44 | -- | -- | 98 | 127 | 546 | 318 | 947 | 500 | -- | 3.2 | 2,380 | 766 | -- | -- |
| 25-64-3 | J. S. Wagley | 100 | 11-11-44 | -- | -- | 84 | 36 | 53 | 266 | 150 | 68 | -- | 3.2 | 608 | 358 | -- | -- |
| 27-02-2 | Frontier Chem. Co. | 167 | 7-15-60 | 54 | -- | 56 | 34 | 46 | 221 | 93 | 63 | 3 | 4.8 | 494 | 280 | 719 | 7.5 |
| 04-3 | Columbia Carbon Co. | 131 | 5-24-44 | -- | -- | 48 | 69 | 71 | 296 | 130 | 128 | -- | -- | 592 | 404 | -- | -- |
| 05-8 | Loop School | 90 | 8- 9-38 | -- | -- | 107 | 136 | 194 | 317 | 565 | 285 | -- | -- | 1,443 | 829 | -- | -- |
| 10-1 | E. H. Jones | 70 | 11- 8-45 | -- | -- | 138 | 66 | 99 | 217 | 282 | 251 | -- | 7.4 | 950 | 616 | -- | -- |
| 13-3 | Mrs. J. D. Cowling | 65 | 8-18-38 | -- | -- | 73 | 73 | 108 | 336 | 244 | 130 | -- | -- | 796 | 480 | -- | -- |
| 15-7 | W. E. Taylor | 160 | 8-11-38 | -- | -- | 651 | 358 | 934 | 171 | 1,378 | 2,520 | -- | -- | 5,925 | 3,100 | -- | -- |
| 20-7 | James Stanley | 104 | 8-10-38 | -- | -- | 213 | 143 | 557 | 268 | 1,078 | 690 | -- | -- | 2,828 | 1,118 | -- | -- |
| 22-3 | Texas Land & Mortgage Company | 81 | 8-12-38 | -- | -- | 111 | 124 | 88 | 293 | 393 | 225 | -- | -- | 1,100 | 787 | -- | -- |
| 25-1 | L. E. Robinson | 77 | 10-23-45 | -- | -- | 59 | 33 | 56 | 280 | 85 | 59 | -- | 4.1 | 516 | 282 | -- | -- |
| 28-5 | Everett King | 70 | 8-16-38 | -- | -- | -- | -- | -- | 329 | 108 | 57 | -- | -- | 512 | -- | -- | -- |

See footnotes at end of table.

Table 2.--Representative chemical analyses of water from primary and secondary aquifers, Region I, Colorado River basin--Continued

| Well | Owner | Depth of well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27-30-7 | University of Texas | 67 | 8-15-39 | -- | -- | 157 | 131 | 196 | 256 | 682 | 310 | -- | -- | 1,602 | 932 | -- | -- |
| 35-1 | J. F. Getrie and O. G. Ritle | 93 | 9- 9-39 | -- | -- | 51 | 19 | 100 | 250 | 112 | 70 | -- | -- | 480 | 207 | -- | -- |
| 40-9 | Dick Knox | 87 | 5-19-36 | -- | -- | 44 | 5 | 93 | 305 | 117 | 104 | -- | -- | 515 | 316 | -- | -- |
| 44-1 | Lera Bottles | 100 | 8- 1-39 | -- | -- | 85 | 44 | 229 | 275 | 347 | 210 | 3.3 | -- | 1,053 | 392 | -- | -- |
| 46-3 | Midland Farms Co. | 67 | 10-14-36 | -- | -- | 89 | 17 | 20 | 256 | 37 | 60 | -- | -- | 349 | 290 | -- | -- |
| 51-4 | University of Texas | -- | 9- 4-36 | -- | -- | 73 | 15 | 96 | 165 | 148 | 116 | -- | -- | 529 | 245 | -- | -- |
| 54-6 | Fay Procter | 52 | 1-15-48 | -- | -- | 112 | 33 | 101 | 268 | 194 | 146 | -- | 8.0 | 818 | 415 | 1,220 | -- |
| 63-7 | City of Midland | -- | 2- -53 | 64 | 0.2 | 92 | 49 | 145 | -- | 283 | 186 | 3.2 | 7 | 900 | 431 | -- | -- |
| 28-01-4 | S. T. Jeffries | 34 | 7-28-38 | -- | -- | 76 | 108 | 482 | 482 | 633 | 395 | 1.1 | 20 | 1,966 | 625 | -- | -- |
| 7 | Fred Henderson | 115 | 7-29-38 | -- | -- | 57 | 62 | 95 | 336 | 193 | 90 | -- | -- | 662 | 398 | -- | -- |
| 10-7 | D. F. Southard | 140 | 6-16-38 | -- | -- | 68 | 62 | 89 | 317 | 231 | 80 | -- | -- | 691 | 423 | -- | -- |
| 25-2 | C. O. Applegate | 95 | 6-14-38 | -- | -- | 85 | 66 | 192 | 336 | 222 | 274 | -- | -- | 1,017 | 486 | -- | -- |
| 26-1 | D. Freeman | 120 | do | -- | -- | 44 | 46 | 101 | 342 | 86 | 90 | 4.7 | -- | 549 | 298 | -- | -- |
| 33-6 | C. C. Slaughter | 15 | 5- 4-36 | -- | -- | 24 | 53 | 506 | 690 | 393 | 285 | -- | -- | 1,607 | 286 | -- | -- |
| 37-1 | Arch C. Ginsley | 158 | 6- 5-36 | -- | -- | 40 | 10 | 89 | 250 | 46 | 58 | -- | -- | 366 | 142 | -- | -- |
| 41-1 | G. T. Hall-Price | 78 | 5-19-36 | -- | -- | 107 | 70 | 199 | 354 | 276 | 290 | -- | -- | 1,119 | 554 | -- | -- |
| 43-7 | H. E. Guerin | 52 | 1-17-36 | -- | -- | 54 | 30 | 224 | 810 | -- | 50 | -- | -- | 763 | 258 | -- | -- |
| 49-4 | Colorado River Municipal Water District | -- | 7-20-60 | 51 | .01 | 102 | 79 | 287 | 246 | 504 | 308 | 2.7 | 13 | 1,530 | 580 | 2,220 | 7.1 |
| 50-1 | H. W. Fulton | 110 | 4- 7-36 | -- | -- | 63 | 46 | 142 | 293 | 184 | 158 | -- | -- | 739 | 346 | -- | -- |
| 52-6 | Mrs. G. Connally, et al. | 80 | 2- 2-36 | -- | -- | 124 | 58 | 208 | 110 | 211 | 490 | -- | -- | 1,146 | 547 | -- | -- |
| 59-7 | H. C. Houston | 175 | 8- 7-61 | 59 | -- | 57 | 39 | 89 | 232 | 142 | 100 | 3.8 | 8.1 | 611 | 302 | 957 | 7.4 |
| 60-6 | Gillean | 118 | 12-13-37 | 31 | 5.0 | 89 | 23 | -- | -- | 80 | 60 | .9 | 31 | 581 | 317 | -- | -- |
| 44-03-7 | Mrs. A. C. Weyman | 66 | 2-16-37 | -- | -- | -- | -- | -- | 195 | 1,362 | 350 | -- | -- | 2,636 | -- | -- | -- |
| 45-08-5 | Ruth Dowlin | 80 | 7- 2-37 | -- | -- | 50 | 24 | 28 | 195 | 60 | 60 | -- | -- | 318 | 225 | -- | -- |
| 8 | Wilson | 40 | 7-31-37 | -- | -- | 364 | 186 | 605 | 268 | 937 | 1,220 | -- | -- | 3,528 | 1,675 | -- | -- |
| | | | | | | | Edwards-Trinity (Plateau) Aquifer | | | | | | | | | | |
| 27-52-7 | University of Texas | -- | 8-20-36 | -- | -- | 42 | 24 | 42 | 146 | 67 | 76 | -- | -- | 323 | 205 | -- | -- |

See footnotes at end of table.

Table 2.--Representative chemical analyses of water from primary and secondary aquifers, Region I, Colorado River basin--Continued

| Well | Owner | Depth of well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27-59-6 | Ector Water Co. | -- | 7-19-60 | 43 | -- | 77 | 12 | 41 | 239 | 64 | 42 | 1.8 | 6.6 | 416 | 242 | 631 | 7.3 |
| 63-7 | C. Scharbauer | 90 | 7-22-57 | -- | -- | 76 | 9 | 31 | 244 | 37 | 38 | -- | -- | 311 | 225 | -- | -- |
| 44-10-1 | D. L. Hutt | 104 | 7-14-37 | -- | -- | 107 | 21 | 52 | 275 | 99 | 98 | -- | -- | 512 | 353 | -- | -- |
| 4 | Phillips Petroleum Co. | -- | 7-20-60 | 11 | -- | 149 | 69 | 3,610 | 354 | 1,800 | 4,500 | -- | -- | 10,300 | 656 | 15,200 | 7.1 |
| 8 | J. W. Driver | 90 | 3-30-37 | -- | -- | 168 | 32 | 71 | 226 | 430 | 50 | -- | -- | 862 | 550 | -- | -- |
| 17-4 | Midkiff Bros. | 165 | 6-15-37 | -- | -- | 100 | 24 | 35 | 73 | 307 | 32 | -- | -- | 534 | 350 | -- | -- |
| 45-04-1 | City of Goldsmith | 165 | 5-11-60 | 33 | -- | 117 | 25 | 101.7 | 202 | 250 | 110 | 1.8 | 42 | 833 | 395 | 1,200 | 6.9 |
| 12-4 | J. E. Parker | 189 | 4-27-37 | -- | -- | 185 | 38 | 106 | 189 | 526 | 104 | -- | -- | 1,050 | 618 | -- | -- |
| 6 | Fred A. Goswick | 110 | 7-19-60 | 28 | -- | 80 | 17 | 66 | 214 | 155 | 41 | 1.8 | 18 | 515 | 270 | 782 | 7.3 |
| 13-3 | Odessa N. Gasoline Co. | -- | -- | 50 | -- | 418 | 139 | 905 | 180 | 442 | 2,110 | -- | -- | 4,150 | 1,610 | 6,930 | 7.2 |
| 3 | J. E. Bageley | 72 | 5-14-37 | -- | -- | -- | -- | -- | 268 | 269 | 72 | -- | -- | 714 | -- | -- | -- |
| 14-8 | Dora Roberts | 108 | 4- 7-37 | -- | -- | -- | -- | -- | 110 | 204 | 52 | -- | -- | 460 | -- | -- | -- |
| 24-2 | A. C. Francis | 69 | 7-30-37 | -- | -- | 229 | 29 | 62 | 226 | 551 | 48 | -- | -- | 1,030 | 693 | -- | -- |
| | **Edwards-Trinity (High Plains) Aquifer** | | | | | | | | | | | | | | | | |
| 24-27-2 | Water Flood Assoc. | 384 | 5-24-61 | 12 | -- | 17 | 8.6 | 556 | 254 | 388 | 475 | 1.8 | 1.0 | 1,620 | 78 | 2,620 | 7.6 |
| 44-8 | George R. Alexander | 357 | 6-28-44 | -- | -- | 6.6 | 4.4 | 416 | 356 | 297 | 239 | -- | -- | 1,140 | 34 | -- | -- |
| 56-7 | A. R. Brownfield | 415 | 6-23-44 | -- | -- | 10 | 7.3 | 1,020 | 586 | 436 | 950 | -- | 2.8 | 2,710 | 55 | -- | -- |
| 61-5 | Wellman Water Works | 242 | 7-15-60 | 9.5 | -- | 11 | 7.1 | 673 | 386 | 456 | 510 | 2.6 | 3.5 | 1,860 | 56 | 3,080 | 7.9 |
| 28-01-2 | W. P. Moore | 206 | 7-29-38 | -- | -- | 318 | 179 | 589 | 226 | 923 | 3,320 | -- | -- | 5,450 | 1,530 | -- | -- |
| 5 | W. H. Heinen | 107 | 7-28-38 | -- | -- | 174 | 34 | 35 | 287 | 230 | 94 | -- | 55 | 763 | 576 | -- | -- |
| 02-6 | L. F. Southerland | 119 | 7-22-38 | -- | -- | 73 | 51 | 659 | 366 | 584 | 650 | -- | -- | 2,197 | 391 | -- | -- |
| 8 | B. E. Evans Estate | Spring | 6-29-38 | -- | -- | 72 | 46 | 113 | 238 | 169 | 160 | -- | 20 | 697 | 368 | -- | -- |
| 03-4 | G. C. Aten | 55 | 7-22-38 | -- | -- | 66 | 50 | 145 | 293 | 149 | 190 | 6.0 | -- | 758 | 371 | -- | -- |
| 8 | John Stevens | 214 | 6-29-48 | 8 | -- | 26 | 16 | 1,220 | 336 | 551 | 1,340 | -- | 5 | 3,360 | 131 | -- | -- |
| 04-7 | C. B. Hays | 60 | do | 36 | -- | 56 | 42 | 91 | 292 | 128 | 74 | -- | 16 | 600 | 312 | -- | -- |
| 12-5 | C. O. Carmach | Spring | 6-29-61 | 67 | -- | 225 | 84 | 201 | 334 | 268 | 538 | 3.0 | 31 | 1,780 | 970 | 2,600 | 6.8 |

See footnotes at end of table.

Table 2.--Representative chemical analyses of water from primary and secondary aquifers, Region I, Colorado River basin--Continued

| Well | Owner | Depth of well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Santa Rosa Aquifer | | | | | | | | | |
| 27-09-8 | Mid American Pipeline Co. | 7,300 | 6- 1-60 | -- | -- | -- | -- | 1,130 | 378 | 1,650 | 358 | -- | -- | 3,360 | 70 | 4,800 | 8.0 |
| 43-2 | University of Texas | 1,200-1,300 | 12-12-56 | 12 | -- | 15 | 6.8 | 969 | 498 | 838 | 630 | -- | -- | 2,720 | 65 | 4,150 | 8.2 |
| 53-5 | David Frasken | 1,605 | 7-12-56 | -- | -- | 96 | 13 | -- | -- | 298 | 384 | -- | -- | 1,554 | -- | -- | -- |
| 28-08-8 | M. B. Noel | 350 | 7-22-60 | 9.5 | -- | 3 | 1.7 | 582 | 701 | 338 | 240 | 5 | 1 | 1,530 | 14 | 2,410 | 8.1 |
| 24-9 | Mary R. Towle | 418 | 3- 8-56 | 13 | -- | 33 | 16 | 1,304.6 | 460 | 331 | 1,590 | -- | 1.0 | 3,820 | 148 | 5,870 | 8.1 |
| 9 | Mrs. J. L. Birdwell | 200 | 7-30-58 | 11 | -- | 4.8 | 2.6 | 206.2 | 426 | 66 | 37 | 2.0 | -- | 539 | 22 | 886 | 8.2 |
| 32-6 | Lelland McCarthy | 150 | 6-30-61 | 21 | -- | 355 | 224 | 290 | 396 | 1,570 | 330 | .4 | 13 | 3,000 | 1,810 | 3,720 | 6.9 |
| 40-6 | A. R. Foster | 300 | 7-21-48 | 3.5 | -- | 13 | 9.4 | 952 | 516 | 454 | 850 | -- | .5 | 2,560 | 71 | 4,280 | -- |
| 29-09-8 | Mrs. E. Lambert | 273 | 7-23-60 | 20 | -- | 127 | 34 | 108 | 243 | 48 | 310 | .7 | 4.0 | 880 | 457 | 1,410 | 7.0 |
| 17-2 | City of Snyder | 160 | 5-22-46 | -- | -- | 54 | 22 | 44 | 304 | 24 | 30 | -- | 6.4 | 364 | 226 | -- | -- |
| 18-7 | Ben Thompson | 104 | 6-22-46 | -- | -- | 42 | 22 | 10 | 138 | 26 | 54 | -- | 2.5 | 341 | 196 | -- | -- |
| 26-8 | China Grove Gin Co. | 55 | 6-21-46 | -- | -- | 68 | 21 | 189 | 252 | 121 | 89 | -- | 260 | 856 | 256 | -- | -- |
| 33-9 | Ted Enderly | 100 | 5-16-46 | -- | -- | 192 | 62 | 108 | 292 | 406 | 217 | -- | 0 | 1,350 | 734 | -- | -- |
| 34-8 | Noble Walker | 188 | 5- 6-53 | 20 | -- | 87 | 50 | 50 | 331 | 192 | 38 | 1.0 | 0 | 612 | 422 | 933 | 7.8 |
| 42-8 | Tom Killian | 126 | 5- 8-53 | 24 | -- | 135 | 45 | 79 | 239 | 116 | 220 | .8 | 70 | 914 | 522 | 1,390 | 7.5 |
| 44-1 | J. B. Mahon | 205 | 5- 5-60 | 15 | -- | 61 | 30 | 27 \| 2.5 | 296 | 36 | 36 | -- | 1.2 | 359 | 276 | 616 | 7.4 |
| 45-13-2 | Pan American Petroleum Co. | 1,230 | 8-29-57 | -- | -- | -- | -- | -- | -- | 811 | 525 | -- | -- | 2,631 | -- | -- | 7.9 |

a/ Includes the equivalent of any carbonate ($CO_3$) present.
b/ Some analyses include the sum of the total constituents; others, about half the bicarbonates.

Waters highly mineralized because of natural causes are associated with areas of shallow water-table conditions, notably areas near water-table lakes and near draws. Chemical analyses indicate the presence of water of poor quality in the vicinity of the Lost Draw complex of Terry, Lynn, and Dawson Counties, Beals Creek, and Mustang Draw. These tributaries of the Colorado River are shown on Plate 1. Where the water table is at or very near the land surface, evapotranspiration processes produce highly mineralized ground waters by the concentration of residual salts. Areas of highly mineralized ground water result artificially from surface disposal of oil-field brines and other industrial wastes and possibly from leakage of brine from oil wells. Man-made contamination is a matter of special concern, particularly because of its far-reaching effects. A contaminant, once introduced in the aquifer, spreads from the contaminated area, moving in about the same direction and at the same rate as the main body of ground water in the aquifer. Hence, water may be rendered unfit for most beneficial uses over a considerably large area, and because of the slow rate of movement, the effects of contamination may persist for many decades.

Unlike surface-water supplies, the contamination of ground-water reservoirs can be detected only at points of reservoir discharge. In the Ogallala aquifer in Region I of the Colorado River basin, these points of discharge include springs, seeps, and wells. Most of the ground water is discharged through the relatively high-capacity wells; therefore, as well development and pumpage increase, the incidence of contamination can be expected to increase.

## Utilization and Development

Approximately 92 percent of the total ground water pumped in Region I of the Colorado River basin in 1960 was produced from the Ogallala aquifer; this represents almost 84 percent of the water pumped from the entire Colorado River basin in 1960. The Ogallala aquifer is a source of water for towns, communities, industries, irrigators, and oil-field camps, as well as for domestic and live-stock wells.

The history of irrigation development--irrigation accounts for about 90 percent of the water pumped in 1960 from the Ogallala--dates back to the early 1900's. The earliest reported large-capacity irrigation well in Region I was completed in Martin County in 1918. From data presented by Alexander and Lang (1945, p. 4), it is estimated that there were probably no more than 30 irrigation wells in Region I in 1944 and that most of these wells were in Martin and Terry Counties. At the close of World War II, irrigation-well development began increasing rapidly. The 7 years of drouth conditions in the early 1950's accelerated the rate of irrigation-well completion. By the end of 1960 more than 6,000 irrigation wells were developed in the Ogallala aquifer of Region I. In addition to the irrigation development, more than 200 municipal wells and 100 or more industrial wells produced water from the Ogallala aquifer in this region. The locations of these wells are shown on Plate 1.

In 1960 the total pumpage from the Ogallala in the Colorado River basin was approximately 690,000 acre-feet. Of this amount approximately 19,000 acre-feet was pumped for municipal use, 7,000 acre-feet for industrial use, and 660,000 acre-feet for irrigation.

The irrigation pumpage for 1960 was calculated by applying averaged well yields to the average seasonal operating time, as determined by statistical analysis of power-consumption data. The average pumping time in 1960 was 65 days. These figures indicate that an average of 110 acre-feet of water was pumped from each irrigation well in 1960. Pumpage from the Ogallala aquifer in Region I for 1960 is presented, by major drainage subdivisions, in Table 3.

Yields of wells producing from the Ogallala aquifer vary greatly from well to well, with the individual sustained yields of major wells reportedly ranging upward to as much as 2,000 gallons per minute (oral communication, Ed Reed). Most of the wells producing from the aquifer range from about 200 to 900 gpm with an average yield of about 400 gpm. The specific capacities of wells completed in the Ogallala aquifer in Region I are known to range from less than one to more than 100 gpm per foot of drawdown. Averaged specific capacities of Barnes and others (1949, p. 31), as compiled by groups of Ogallala wells in 11 individual counties of the Southern High Plains, range from 14 to 36 gpm per foot of drawdown and average about 25 gpm per foot of drawdown. Specific capacities are governed by well construction as well as by hydraulic properties of the aquifer.

Well casings generally extend to the base of the aquifer and are slotted below the water table. Pumping lifts generally range between 50 and 150 feet although they may exceed 150 feet in some areas.

Concentrated irrigation and municipal well development in the south-central part of Martin County has resulted in dewatering of about 50 percent of the original (1938) saturated section. Extensive declines in water levels and well yields have occurred in the Monahans and Midland Draw areas in Midland County. Continued or additional concentrated pumpage can be expected to cause greater water-level declines and reduction in well yields.

## Ground Water Available for Development

The amount of water available for development from the Ogallala aquifer, as determined during this study, is based on water in storage. About 29,000,000 acre-feet of ground water is in storage in the Ogallala aquifer in Region I of the Colorado River basin, as determined from an estimated average specific yield of 0.15. Not all of this stored water is considered recoverable under present economics and methods of well construction. Assuming that within present economic limits of major well operations 50 to 75 percent of the water in storage could economically be recovered, then 15,000,000 to 20,000,000 acre-feet could be developed from the Ogallala in Region I. About 690,000 acre-feet of ground water was pumped from the Ogallala aquifer in 1960; this represents about 2.5 percent of the estimated volume of water in storage.

It is necessary to point out that not all of the water pumped in 1960 from the Ogallala aquifer was removed from storage; an undetermined amount of irrigation pumpage is returned to the aquifer each year by infiltration. It is also possible that some of the natural discharge which existed prior to large-scale development of the aquifer is now being captured by wells; however, this amount is small in comparison with the total pumpage.

Large amounts of ground water are available for future development in western Gaines County, in southwestern and northwestern Yoakum County, and in parts of south-central Cochran County.

Table 3.--1960 Ground-water pumpage from aquifers in Region I, Colorado River basin

(Pumpage, some of which is estimated, is expressed in acre-feet, and should be considered accurate to no more than two significant figures. Municipal pumpage includes water supplied by privately-owned systems.)

| Use | 1960 Pumpage, by major drainage subdivision | | | | | | | | | Total 1960 pumpage |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 4 | 6 | 7 | 8 | 11 | 15 | 18 | 20 | |
| | | | | | Ogallala Aquifer | | | | | |
| Municipal | 2,430 | -- | -- | -- | 1,486 | 4,290 | 2,210 | 9,060 | -- | 19,476 |
| Industrial | 559 | -- | -- | -- | 807 | 4,356 | 841 | -- | *461 | 7,024 |
| Irrigation | 200,045 | *2,075 | -- | * 81 | 149,949 | 217,000 | *27,721 | *63,925 | *161 | 660,957 |
| Subtotal | 203,034 | 2,075 | -- | 81 | 152,242 | 225,646 | 30,772 | 72,985 | 622 | 687,457 |
| | | | | | Edwards-Trinity (Plateau) Aquifer | | | | | |
| Municipal | -- | -- | -- | -- | -- | -- | 2,702 | -- | -- | 2,702 |
| Industrial | -- | -- | -- | -- | -- | -- | 5,821 | -- | -- | 5,821 |
| Irrigation | -- | -- | -- | -- | -- | -- | 120 | -- | -- | 120 |
| Subtotal | -- | -- | -- | -- | -- | -- | 8,643 | -- | -- | 8,643 |
| | | | | | Edwards-Trinity (High Plains) Aquifer | | | | | |
| Municipal | -- | -- | -- | -- | 134 | -- | -- | -- | -- | 134 |
| Industrial | 191 | -- | -- | -- | -- | -- | -- | -- | -- | 191 |
| Irrigation | 657 | 1,590 | -- | -- | -- | -- | -- | -- | -- | 2,247 |
| Subtotal | 848 | 1,590 | -- | -- | 134 | -- | -- | -- | -- | 2,572 |
| | | | | | Santa Rosa Aquifer | | | | | |
| Municipal | -- | -- | 113 | * 116 | -- | -- | -- | -- | -- | 229 |
| Industrial | -- | -- | 537 | -- | -- | 4,640 | 1,964 | -- | -- | 7,141 |
| Irrigation | -- | -- | *6,710 | *30,596 | -- | -- | -- | -- | --- | 37,306 |
| Subtotal | -- | -- | 7,360 | 30,712 | -- | 4,640 | 1,964 | -- | -- | 44,676 |
| | | | | | Other Aquifers† | | | | | |
| Municipal | -- | -- | 14 | -- | -- | -- | -- | -- | -- | 14 |
| Industrial | -- | 154 | -- | -- | -- | -- | -- | -- | -- | 154 |
| Irrigation | -- | 307 | -- | -- | 1,517 | -- | -- | -- | -- | 1,824 |
| Subtotal | -- | 461 | 14 | -- | 1,517 | -- | -- | -- | -- | 1,992 |
| | | | | | Summary of Pumpage in Region I | | | | | |
| Municipal | 2,430 | -- | 127 | 116 | 1,620 | 4,290 | 4,912 | 9,060 | -- | 22,555 |
| Industrial | 750 | 154 | 537 | -- | 807 | 8,996 | 8,626 | -- | 461 | 20,331 |
| Irrigation | 200,702 | 3,972 | 6,710 | 30,677 | 151,466 | 217,000 | 27,841 | 63,925 | 161 | 702,454 |
| Total | 203,882 | 4,126 | 7,374 | 30,793 | 153,893 | 230,286 | 41,379 | 72,985 | 622 | 745,340 |

* Figure entirely or partly for 1958 (Texas Board of Water Engineers, 1960b).

† Chinle Formation, Cretaceous rocks (outliers), and alluvium.

Both quantitative and qualitative problems may occur in developing water from the Ogallala aquifer. Limited saturated thickness in some areas of the aquifer will prevent extensive well development in these areas. Pumpage in excess of recharge subjects the aquifer to eventual depletion. Industrial wastes and oil-field brines which are disposed into unlined earthen pits could enter the aquifer and seriously restrict present and future development of ground-water supplies in several areas of Region I.

## Edwards-Trinity (Plateau) Aquifer

The Edwards-Trinity (Plateau) aquifer in Region I of the Colorado River basin occurs in the extreme southern end of the region and extends from Andrews County through Howard County. To the north the aquifer is arbitrarily terminated where Edwards and associated limestones are absent in the subsurface and the Trinity Group sands are indistinguishable from the overlying Ogallala sediments. The extent of the Edwards-Trinity (Plateau) aquifer in Region I of the Colorado River basin is shown on Plate 8. Southwest of the Colorado River basin, the Edwards-Trinity (Plateau) aquifer extends into the Rio Grande basin. The major portion of the Edwards-Trinity (Plateau) aquifer in the Colorado River basin occurs in Region II and will be discussed in greater detail in that section.

North of the selected northern boundary of the Edwards-Trinity (Plateau) aquifer, Cretaceous sediments have been eroded, and are absent in the subsurface beneath the Ogallala Formation. This post-Cretaceous erosion areally separates Cretaceous rocks in the southern part of the Region from Cretaceous rocks in the northern part, and is the basis for the division of the Cretaceous in Region I into two separate aquifers, the Edwards-Trinity (Plateau) and the Edwards-Trinity (High Plains) aquifers. The Edwards-Trinity (High Plains) aquifer is discussed in another part of this report.

The Edwards-Trinity (Plateau) aquifer in Region I consists of saturated Comanche Peak and Edwards Limestones and the saturated Paluxy Sand of the Trinity Group. Some underlying fresh-water-bearing (containing water having less than 3,000 ppm dissolved solids) sands of Triassic age have been included with the aquifer, where they are not readily distinguishable from Cretaceous sediments.

### Geologic Characteristics

In Region I the Edwards and Comanche Peak Limestones are composed of yellow to gray argillaceous limestone. The saturated portion of these limestones is primarily confined to the southeastern corner of Midland County. The remainder of the aquifer over its areal extent is primarily made up of sands of the Trinity Group.

Lithology and thickness of the Trinity Group sands varies. In Howard and Glasscock Counties the Trinity Group, ranging in thickness from 60 to 100 feet, is composed of a white, yellowish, fine-grained, unconsolidated sand, consolidated sandstone, and a basal silica-cemented gravel conglomerate. In places, the sands contain thin beds of clay. The thickness of the Cretaceous deposits in Ector County ranges from 70 to 195 feet, and averages 140 feet. In Ector County the sands comprise approximately 50 percent of the saturated interval with the net thickness ranging from 14 to 107 feet.

The Edwards-Trinity (Plateau) aquifer covers approximately 1,500 square miles in the lower portion of Region I (Plate 8). Cretaceous rocks in much of this area are covered by a thin section of the Ogallala Formation. Areas where Cretaceous rocks are exposed at the surface are shown on Plate 1.

Because Cretaceous rocks were deposited on a highly irregular surface, thick Cretaceous sections are present in some areas, especially in Ector and Midland Counties. The configuration of the pre-Cretaceous land surface is illustrated by Plate 8. The general slope of the base of the Edwards-Trinity (Plateau) aquifer is to the southeast.

Saturated intervals of the Edwards-Trinity (Plateau) aquifer range in thickness from very thin in some places to more than 275 feet in the Pecks Lake collapsed area (grid 44-10) in eastern Midland County. Thin saturated intervals are indicated in some areas in Ector and Midland Counties. Notable saturated intervals, some exceeding 100 feet in thickness, occur in northwestern Ector and south-central Andrews Counties in some conformity to the present surface drainage system.

## Occurrence and Movement of Ground Water

The Edwards-Trinity (Plateau) aquifer throughout its extent in Region I is under water-table conditions. Most of the water in the aquifer is probably contained in the sand portion. Some saturation is known to occur in limestone solution cavities in southeastern Midland County.

Water in this aquifer moves regionally toward the southeast, but locally toward surface drainage areas.

## Recharge and Discharge

The amount of natural recharge to the Edwards-Trinity (Plateau) aquifer of Region I is not known but is probably small. Recharge probably occurs by precipitation on outcrop areas and by water percolating downward through overlying sediments.

Water is discharged from the Edwards-Trinity (Plateau) aquifer naturally by evapotranspiration and artificially through wells. Water-level data indicate that some of the water from the aquifer is being discharged into Johnson Draw in Midland and Glasscock Counties. Artificial discharge from the aquifer in Region I is mostly through major wells, from which approximately 8,600 acre-feet of water was pumped during 1960 (Table 3).

## Water Levels

Depths to water below land surface, in the Edwards-Trinity (Plateau) aquifer, are illustrated on Plate 7. This map indicates depths to water ranging from less than 50 feet in the Johnson Draw area to more than 150 feet in an industrial well field in southwestern Midland County.

Records of water levels in approximately 21 wells in grid 27-59, for the period 1949 to 1959, showed a maximum decline of about 19 feet. The average water-level decline for the period was approximately 9 feet (W. F. Guyton and

Assoc., courtesy Ector Water Co.). Records of water levels in 9 industrial wells producing from Trinity Group sands in southwestern Midland County showed an average water-level decline of approximately 7 feet for the years 1953 through 1959.

### Water-Bearing Characteristics

Results of pumping tests for Edwards-Trinity (Plateau) wells in northwestern Ector County indicate that coefficients of transmissibility range from 144 to 15,300 gpd per foot and average of 3,500 gpd per foot (W. F. Guyton and Assoc., courtesy Ector Water Co.). Higher transmissibilities may be expected for the aquifer in the southeastern part of Midland County where Cretaceous limestones appear to be water bearing.

### Chemical Quality

The quality of the water in the Edwards-Trinity (Plateau) aquifer in Region I varies through wide limits. Chemical analyses of selected water samples collected from wells producing from the Edwards-Trinity (Plateau) aquifer in Region I are presented in Table 2. The dissolved-solids content of a number of water samples is plotted on Plate 8. Well 44-10-401 is producing water from the Pecks Lake slump area. This analysis would seem to indicate that the water contained in these deposits is probably unsuitable for most purposes.

The water in Well 45-13-301 has probably been contaminated, as the chemical analysis in Table 2 indicates, by surficially disposed industrial fluid wastes. Surface disposal of industrial and municipal fluids has reportedly increased the dissolved-solids content of some of the ground water in the Monahans Draw area southeast of Odessa. Surface-disposed industrial waste could seriously jeopardize what little ground water is available for development in this area.

### Utilization and Development

Pumpage from the Edwards-Trinity (Plateau) aquifer in Region I is small in comparison with the pumpage from the Ogallala aquifer. Nevertheless, because the Edwards-Trinity (Plateau) aquifer is the major source of ground water in its area of occurrence in Region I, conditions affecting the water that is stored in the aquifer are extremely important to this study. In 1960, approximately 73 municipal, 120 industrial, and 3 irrigation wells produced water from the Edwards-Trinity (Plateau) aquifer in this region. Twenty-two of the industrial wells were producing potable water for oil-field water-flooding operations.

Approximately 8,600 acre-feet of ground water was pumped from the Edwards-Trinity (Plateau) aquifer in Region I for municipal, industrial, and irrigation purposes during 1960. All of the pumpage, as shown on Table 3, occurred in drainage subdivision 15, and most of the water pumped was used for industrial purposes in the vicinity of Odessa and Goldsmith, in Ector County. In 1960, this aquifer supplied in Region I about 5,800 acre-feet of water for industrial use, 2,700 acre-feet for municipal use, and only about 120 acre-feet for irrigation.

Yields of 60 municipal wells completed in the Edwards-Trinity (Plateau) aquifer, just northwest of Odessa, reportedly range from 30 to 200 gpm. Although specific capacities are not available for these wells, reported specific capacities for wells in the Ector Water Company's well field, which is about 15 miles northwest of the municipal wells (see Plate 1, grid 27-59), range from 0.4 to 14.1 gpm per foot of drawdown, and average 2.1 gpm per foot of drawdown. The yields of 6 industrial wells west of Odessa in grid 45-12 ranged, in 1955, from 38 to 85 gpm; and the yields of 9 industrial wells in southwestern Midland County averaged, in 1959, 166 gpm.

The hydrologic properties of the Trinity Group sands will probably limit future development to spaced-planned, low-yield wells. Declines in water levels have caused considerable reduction in well yields in the city's well field just northwest of Odessa and in the performance of wells in southwestern Midland County. In the Pegasus area of southwestern Midland County a 7-foot decline in water levels was associated with a reduction in well yields of about 31 percent.

The surface disposal of industrial wastes and oil-field brines poses a serious threat to the present and future development of the Edwards-Trinity (Plateau) aquifer in Region I of the Colorado River basin.

### Ground Water Available for Development

Assuming an average specific yield of 0.15, it is estimated that approximately 3,400,000 acre-feet of ground water is stored in the Edwards-Trinity (Plateau) aquifer in Region I. Because of the methods of well construction now employed and the economics of well operation, the complete dewatering of the aquifer does not appear likely. Thus, assuming that from 50 to 75 percent of the ground water in storage is recoverable through wells, on the order of 1,700,000 to 2,500,000 acre-feet of water would be available for development from the Edwards-Trinity (Plateau) aquifer in Region I. In addition an undetermined, but probably small, amount of water is available from natural recharge on a perennial basis.

An estimated 500,000 acre-feet of ground water stored in the Peck's Lake slump area (grid 44-10) is probably unfit for most uses and, therefore, has not been considered in the availability-from-storage values presented above.

The apparently low transmissibility of the Edwards-Trinity (Plateau) aquifer in Region I precludes the possibility of obtaining wells with large yields. Optimum development will possibly be through a system of closely-spaced, low-yield wells.

## Secondary Aquifers

### Edwards-Trinity (High Plains) Aquifer

The Edwards-Trinity (High Plains) aquifer in Region I of the Colorado River basin extends across the northern portion of the region from central Gaines, northern Dawson, and northern Borden Counties northward, and embraces an area of approximately 4,750 square miles. The southern extent of the aquifer is selected where Cretaceous strata are apparently absent in the subsurface because of post-Cretaceous erosion. Cretaceous sediments south of this boundary and north of the Edwards-Trinity (Plateau) aquifer are confined to small isolated remnants that are not easily distinguishable form the overlying Ogallala deposits and are, therefore, included with the Ogallala aquifer (see Plate 4). The Edwards-Trinity (High Plains) aquifer is arbitrarily terminated at the Texas-New Mexico State line on the west and at the divide between the Brazos and Colorado River basins on the north. The eastward extent of the aquifer corresponds to the eastward-facing escarpment of the High Plains in Borden and Dawson Counties. The extent of the Edwards-Trinity (High Plains) aquifer is shown on Plate 8.

The Edwards-Trinity (High Plains) aquifer consists of permeable strata of the Trinity and Fredericksburg Groups, which are the Paluxy Sand and in places saturated Comanche Peak and Edwards Limestones.

## Geologic Characteristics

In Region I, the Paluxy Sand portion of the Edwards-Trinity (High Plains) aquifer occurs generally between 300 and 400 feet below the land surface, and is composed primarily of fine- to medium-grained, well sorted, white quartz sand. A review of 41 logs of wells penetrating the Paluxy Sand section indicated a net porous sand interval ranging in thickness from 15 to 60 feet and averaging about 30 feet. The Paluxy Sand, deposited upon Triassic bedrock, grades upward into the usually yellow-colored arenaceous clay of the Walnut Clay. These strata are overlain by argillaceous limestone of the Comanche Peak and Edwards Limestones. These rocks are in turn overlain by the primarily blue-colored Kiamichi Clay except in northeastern Dawson and northwestern Borden Counties, where the Comanche Peak and Edwards Limestones are at or near the surface. The relatively thick Kiamichi Clay, which forms an effective aquiclude between the Ogallala aquifer and the Paluxy Sand portion of the Edwards-Trinity (High PLains) aquifer, is overlain in most places by thin clay and limestone beds of the Washita Group. In the deep subsurface of the High Plains, Comanche Peak and Edwards Limestones are thin and are not known to contain porous or permeable intervals.

In an area of about 150 square miles in the northeastern corner of Dawson County and northwestern corner of Borden County, the Kiamichi Clay is either missing or very thin. In this area the Comanche Peak and Edwards Limestones have sufficient permeability to supply water to irrigation wells. The configuration of the base of the Edwards-Trinity (High Plains) aquifer, shown on Plate 8, illustrates the irregular eroded surface of the Triassic bedrock upon which the Cretaceous sediments were deposited, and indicates the presence of several ancient buried channels traversing the area from northwest to southeast. These channels, which occur in the Triassic bedrock, closely resemble the present-day drainage network of the High Plains. In general, the slope of the base of the Edwards-Trinity (High Plains) aquifer is to the southeast.

The geologic section along the axis of the Colorado River basin, Plate 4, shows the relation of the Edwards-Trinity (High Plains) aquifer to the other aquifers of Region I.

## Occurrence and Movement of Ground Water

Ground water in the Paluxy Sand portion of the Edwards-Trinity (High Plains) aquifer probably exists under artesian conditions throughout most of the aquifer's extent in Region I, and is probably moving southeasterly in some conformity with the slope of the base of the aquifer.

In northeastern Dawson and northwestern Borden Counties, ground water in the Comanche Peak and Edwards Limestones is under water-table conditions, and occurs in solution channels of the limestones which are hydraulically separated from the underlying Paluxy Sand by the Walnut Clay aquiclude. Water in these limestones appears to be moving in a south-southeasterly direction, and issues as springs and seeps along the eastern escarpment of the High Plains in Borden County.

### Recharge and Discharge

Recharge to the Paluxy Sand portion of the Edwards-Trinity (High Plains) aquifer probably occurs in the areas west of Region I where the Paluxy subcrops beneath saturated Ogallala deposits. Quality-of-water data indicate that the Paluxy Sand portion also receives some recharge from the Lost Draw complex, and the alkaline lake areas, within the Brazos River basin in Lynn County. Natural recharge to the Comanche Peak and Edwards Limestones portion of the aquifer in northeastern Dawson and northwestern Borden Counties probably occurs as infiltration through the thin overlying Ogallala sediments; however, much of the recharge is probably derived through the more than 28 recharge wells completed in this portion of the aquifer in Borden County. These wells, about 30 to 70 feet deep, are located in playa lake depressions. Some of the wells are equipped with screens or slotted casing extending above the bottoms of the lake beds for the purpose of screening out some of the larger suspended materials in the recharge water. Despite these precautionary measures, considerable material accumulates in the wells, and residents in the area report that after heavy rains, water produced from domestic wells completed in the same reservoir usually contains visible suspended solids.

Water moving through the Paluxy Sand portion of the Edwards-Trinity (High Plains) aquifer is probably being discharged into the overlying Ogallala aquifer at the terminus of the Edwards-Trinity (High Plains) aquifer beneath the Ogallala deposits in Gaines and Dawson Counties. Springs at the base of the eastern escarpment in Borden County also account for some of the natural discharge from this aquifer. Water is naturally discharged from the Comanche Peak and Edwards Limestones through numerous seeps and springs at the escarpment in Dawson and Borden Counties. Approximately 2,600 acre-feet of water was pumped from the Edwards-Trinity (High Plains) aquifer for municipal, industrial, and irrigation purposes in 1960.

### Water Levels

During the summer of 1960, depths to water in 8 wells penetrating the Comanche Peak and Edwards Limestones portion of the aquifer ranged from 27 to 49 feet below land surface. Water levels throughout the extent of this section of the Edwards-Trinity (High Plains) aquifer are generally less than 50 feet below land surface.

Water in the Paluxy Sand portion of the Edwards-Trinity (High Plains) aquifer is under artesian pressure and rises above the top of the aquifer when penetrated by wells. In some places the hydraulic head is sufficient to cause the water in the wells to rise above the base of the Ogallala Formation. A well completed in the Paluxy Sand portion of the aquifer in grid 24-61 was flowing 2 1/2 gpm when measured in 1944.

### Water-Bearing Characteristics

Data on the hydraulic characteristics of the Edwards-Trinity (High Plains) aquifer are not available. However, it is suspected that the coefficients of transmissibility of the Paluxy Sand portion of the aquifer are relatively low because the thickness of the sand is generally small. Considerably higher transmissibilities might be expected in the saturated limestones in northeastern Dawson and northwestern Borden Counties.

### Chemical Quality

Selected chemical analyses of water samples from the Edwards-Trinity (High Plains) aquifer of Region I are presented in Table 2. The dissolved solids of a number of water samples and locations of the wells from which the water samples were collected are shown on Plate 8. Dissolved-solids content of water in the Paluxy Sand is generally higher than that in the overlying Ogallala aquifer. East of Lost Draw in Dawson, Lynn, and southern Terry Counties, water in the Paluxy is usually unsuitable for most beneficial uses.

### Utilization and Development

Pumpage from the Edwards-Trinity (High Plains) aquifer in Region I is extremely small in comparison with pumpage from the Ogallala aquifer. About 2,600 acre-feet of water was pumped from the Edwards-Trinity (High Plains) aquifer for municipal, industrial, and irrigation purposes during 1960. Of this amount, about 2,200 acre-feet was pumped from about 75 irrigation wells completed in the Comanche Peak and Edwards Limestones portion. About 190 acre-feet was pumped by 3 industrial wells, and about 130 acre-feet was pumped by 1 municipal well. The pumpage from the Edwards-Trinity (High Plains) aquifer, by major drainage subdivisions, is presented in Table 3.

An industrial well located in grid 24-44-7 of Yoakum County produces about 65 gpm from the Paluxy Sand portion of the Edwards-Trinity (High Plains) aquifer with an apparent specific capacity of about 1.1 gpm per foot of drawdown. Leggat (1952, p. 21) reported that a well completed in the Comanche Peak and Edwards Limestones portion of the aquifer in northeastern Dawson County produced 810 gpm with only 0.69 foot of drawdown, indicating a specific capacity of 1,175 gpm per foot of drawdown. Irrigation wells completed in this aquifer in northeastern Dawson County and northwestern Borden County have an estimated average yield of approximately 100 gpm.

### Ground Water Available for Development

In order to estimate the magnitude of water available from the Edwards-Trinity (High Plains) aquifer, the following assumptions were made. For the Paluxy Sand portion of the aquifer, an average sand thickness of 30 feet and a specific yield of 0.15 were assumed. A 250-square-mile area of poor-quality water in the eastern part of the region was not included in the calculations; thus the area considered embraces approximately 4,500 square miles. For the Comanche Peak and Edwards Limestones portion, a specific yield of 0.015 was assumed and a saturated section of approximately 20 feet was used. From the above assumptions, approximately 13,000,000 acre-feet of water is estimated to be stored in the Edwards-Trinity (High Plains) aquifer. Because of the thin saturated section and considering that well-construction methods and economics of well operation prohibit the complete dewatering of the saturated interval, it is assumed that about 25 percent of the water in storage can be produced. Therefore, it is estimated that an order of magnitude of 3,300,000 acre-feet of water could be developed from the Edwards-Trinity (High Plains) aquifer. These estimates are made on the assumption of aquifer depletion and do not account for any recharge. In addition to the probable small amount of natural recharge, it appears that in the Comanche Peak and Edwards Limestones portion of the aquifer in northeastern Dawson County and northwestern Borden County, there is a notable additional quantity of water available on a perennial basis through the application of the recharge wells.

## Santa Rosa Aquifer

The Santa Rosa Formation is present either at the surface or in the subsurface throughout Region I, except in a small area along the Colorado River in southeastern Mitchell County. It crops out east of the Colorado River in parts of Scurry, Mitchell, and Nolan Counties. The areas in which the Santa Rosa Formation is known to produce usable water in Region I, and therefore designated for the purposes of this report as the Santa Rosa aquifer, occur only in the eastern and western parts of the region, as shown on Plate 9. Water containing up to 4,000 ppm dissolved solids has been included as usable in the Santa Rosa aquifer where it occurs in western Gaines County, central Andrews County, and central Ector County. In the eastern part of Region I the Santa Rosa aquifer occurs in the central part of Scurry County, central and northeastern Mitchell County, and the small part of Nolan County in this region. The aquifer, as defined in this report, includes a small area of Region II in southeastern Mitchell and southwestern Nolan Counties. This area has been included on Plate 9 and is considered in the discussion of this aquifer in Region I. In some parts of the aquifer's extent, rocks of Triassic age other than those of the Santa Rosa Formation, and rocks of Cretaceous age have been included with the Santa Rosa aquifer where they are hydraulically associated with the Santa Rosa.

### Geologic Characteristics

In general, the Santa Rosa Formation is composed of interbedded lenses of sand, hard sandstone, gravel, and red, green, and blue shale. Near the base of the formation, in a few places a tightly-cemented quartz conglomerate occurs as either one thick bed or several thin beds separated by sandy intervals. The Santa Rosa was deposited upon an eroded surface of older Triassic and Permian rocks under non-marine conditions. The individual sand beds of the Santa Rosa Formation are highly lenticular and their physical and hydrologic characteristics can change within short distances. Sand and gravel constitute approximately 34 percent of the formation's thickness in most of the region; however, drillers' logs indicate that about 60 percent of a 110-foot section of the Santa Rosa aquifer in Mitchell and Nolan Counties consists of sand or gravel. The thickness of the Santa Rosa aquifer ranges from a featheredge in its eastern extremity to about 400 feet in the western part of the region. The average thickness is about 200 feet.

On the eastern side of Region I, the Santa Rosa aquifer dips southwest at a rate of approximately 50 feet per mile in Scurry County and west-northwest at 25 to 35 feet per mile in Mitchell County. On the western side of the region, the Santa Rosa aquifer dips to the northeast. Contours on the base of the Santa Rosa Formation and associated sands (Plate 9) illustrate a north-trending basin. The Santa Rosa thickens toward the axis of the basin.

## Occurrence and Movement of Ground Water

Ground water in the Santa Rosa occurs under artesian conditions throughout the study area except in and near its outcrop where it is under semi-artesian or water-table conditions.

The Santa Rosa aquifer in the eastern part of Region I is actually made up of two hydraulically distinct water-bearing units in northern Mitchell and Scurry Counties, a lower and an upper sand, separated by a shale or clay section. In east-central Mitchell and Nolan Counties only the lower reservoir is present as the source of water for many of the irrigation wells in this area, and ground water generally moves toward the Colorado River. In parts of Scurry County, the water moves generally toward the Colorado River but locally toward small tributaries.

In the western part of Region I, ground water in the Santa Rosa aquifer is assumed to be moving generally in an easterly direction.

## Recharge and Discharge

In the eastern part of Region I, recharge or replenishment of water in the Santa Rosa aquifer is probably derived from regional precipitation on the sand and gravel outcrop areas of the formation, from downward percolation through Tertiary materials overlying the aquifer above the water table in northwestern Nolan County, and through subcrop areas through overlying and contiguous Cretaceous rocks in parts of south-central and southwestern Nolan County. Precipitation on the outcrop areas probably percolates directly to the water table. Where Tertiary rocks overlie the Santa Rosa Formation in northwestern Nolan County, the sediments are above the regional water table but appear to constitute an effective recharge conduit to saturated sand and gravel of the aquifer. Precipitation on Cretaceous outcrops which overlie the Santa Rosa Formation is absorbed and moves southwest, west, and northwest, ultimately moving into the Santa Rosa aquifer in areas where the Santa Rosa Formation is in contact with the Paluxy Sand.

Ground water is being discharged from the Santa Rosa aquifer in the eastern part of Region I through springs and seeps at its eastern extremity in Mitchell, Nolan, and Scurry Counties, and in outcrop areas within the Brazos River basin. Water is lost also by evaporation from areas where the water table is near the land surface, and by transpiration of plants having roots that extend to or through the capillary fringe above the water table. Pumpage from wells provides for the discharge of some of this aquifer's water; this pumpage is primarily confined to Mitchell, Nolan, and Scurry Counties (Plate 1).

In the western part of Region I, the primary recharge areas are probably in the Santa Rosa outcrop in New Mexico and in the adjacent Rio Grande basin where sands of the Santa Rosa Formation are truncated against overlying saturated sediments.

Methods of discharge from the Santa Rosa aquifer are somewhat obscured in the western part of Region I; however, water-quality zonation suggests that some ground water is being discharged from the aquifer into the overlying Chinle Formation.

### Water Levels

In the eastern part of the Santa Rosa aquifer, depths to water range from the land surface in the areas of springs and seeps to about 300 feet below land surface in northwestern Scurry County. Water-level fluctuations in 16 wells in Scurry County, for the period 1956 through 1961, range from a 4.8-foot decline in one well to a 7.5-foot rise in another well, giving a net average rise of 0.73 foot per well. In Mitchell and Nolan Counties, hydrographs of irrigation wells show a close correlation between annual precipitation and water levels in the aquifer; over much of the area little or no annual decline occurs in irrigation wells when normal or greater than normal precipitation occurs. However, data are not sufficient to determine the magnitude of seasonal fluctuations of the water table in the area.

In the western area, water levels in the Santa Rosa aquifer range between 400 and 600 feet below land surface. Annual water-level measurements, however, have not been made in wells penetrating the aquifer in this area.

### Water-Bearing Characteristics

The analysis of pumping-test data on a municipal well at Snyder indicated coefficient of transmissibility values ranging from 1,520 to 6,000 gpd per foot, averaging 3,500 gpd per foot. Storage-coefficient values ranged from 0.0013 to 0.0018. This well was 227 feet deep and thus penetrated only the upper sands of the Santa Rosa aquifer. Although aquifer tests have not been made on the lower reservoir, which generally produces more water than the upper sands, the fact that wells in one area have far greater yields than those producing from a much greater saturated thickness in other areas indicates that the permeability of the aquifer varies greatly.

In the western part of the aquifer, no aquifer tests were made of the Santa Rosa.

### Chemical Quality

Chemical quality of water in the Santa Rosa aquifer varies widely in both the upper and lower zones and from east to west. Plate 9 shows the distribution of more than 50 selected chemical analyses of water produced from the Santa Rosa Formation. This plate illustrates the water-quality zonation in the formation. Representative chemical analyses from the Santa Rosa aquifer are presented in Table 2.

In the eastern part of Region I, dissolved solids range from about 300 ppm at the Colorado River basin's eastern boundary to more than several thousand ppm toward the western extent of fresh water. In an area extending about 10 or 15 miles west from the basin's eastern boundary, water of chemical quality acceptable for municipal, industrial, or irrigation use occurs in the Santa Rosa. Although this water greatly exceeds hardness recommendations for municipal use, it meets all other municipal requirements. It is also suitable for irrigation. For industrial purposes, hardness, which is related to scale formation, is excessive, and the water will probably require treatment in order to be used in boilers. In Scurry County, water in the upper part of the Santa Rosa aquifer is acceptable for most uses; however, near Colorado City, in Mitchell County, the chemical quality of water in these upper sands is so poor that they had to be cased off in Colorado City's wells. There is a notable deterioration in the quality of water in the basal part of the Santa Rosa aquifer west of the Colorado River in Mitchell County.

In the future, extensive well development in the eastern part of the region near the interface of the fresh and brackish water in the Santa Rosa aquifer may cause movement of poor-quality water into the fresh-water section. Oil field repressuring operations could create extensive subsurface contamination through leaky and improperly cased wells. In some areas surface disposal of industrial fluid wastes are jeopardizing the underlying fresh-water-bearing section. Some encroachment of salt water into an irrigation well located fairly close to the east bank of the contaminated Colorado River in an area just north of Colorado City has been reported and is substantiated by chemical analyses, but it is not known whether the salt is derived from the river or from proximity to the fresh-salt water interface. It is likely that intensive development of water in this area would result in a greater degree of encroachment. Some evidence exists from previous studies that the sulfate content of water in the Colorado City area tended to increase with the lowering of water levels caused by pumping in the old city wells, but it is not known whether this is generally true of the basal part of the aquifer over the area.

In the western part of Region I where the Santa Rosa aquifer occurs, water quality deteriorates toward the axis of the structural basin. Water from the Santa Rosa in this area generally contains more than 2,000 ppm dissolved solids and is suitable only for domestic and livestock uses in water-short areas, or for water-flooding operations of the petroleum industry.

## Utilization and Development

Approximately 6 percent of the total ground-water pumpage in Region I of the Colorado River basin in 1960 was from the Santa Rosa aquifer. This aquifer supplies water for small towns and communities, for industries, and for irrigation, as well as for domestic and livestock-watering purposes.

Pumpage from the Santa Rosa aquifer for 1960 is presented, by major drainage subdivisions, in Table 3 for Region I and in Table 5 for that small portion of the aquifer which occurs in Region II. The total pumpage from the Santa Rosa aquifer in 1960 amounted to approximately 45,000 acre-feet. Of this total approximately 230 acre-feet was pumped for municipal use, 7,000 acre-feet for industrial use, and 37,000 acre-feet for irrigation. Irrigation pumpage figures are for the year 1958 and were obtained from Bulletin 6018 (Texas Board of Water Engineers, 1960b). Irrigation pumpage is confined to Scurry, Mitchell, and Nolan Counties in the eastern part of Region I, whereas the industrial pumpage is practically all in the western part of Region I.

Water used in water-flooding operations has been included with pumpage for industrial use only when it contains less than 4,000 ppm dissolved solids. In addition to the fresh water used for water-flooding, highly mineralized water from the Santa Rosa Formation is used for water-flooding operations in Borden, Cochran, Denton, Hockley, Howard, Midland, Mitchell, and Terry Counties.

Yields of wells producing from the Santa Rosa aquifer in the eastern part of Region I range from 35 to 1,150 gpm, and average about 250 gpm. Specific capacities of wells in the eastern part of Region I range from 0.2 to 8.0 gpm per foot of drawdown and average about 3 or 4 gpm per foot of drawdown.

In the western part of Region I, yields of wells range from 23 to 263 gpm and average about 100 gpm.

Wells completed in the Santa Rosa aquifer are commonly cased to bottom with slotted pipe opposite the saturated zones, but many are cased only through the upper zones of clay and shale, which are subject to caving, and the remainder of the hole is left open. Most of the irrigation wells are equipped with line shaft turbine pumps, although there are a few generally small, submergible electric turbine pumps in use. The line shaft turbine pumps are usually driven by butane or natural gas engines ranging from 5 to 50 horsepower; however, electric motors are usually installed on small- to medium-capacity pumps, probably averaging about 15 horsepower. In Mitchell and Nolan Counties, pump intakes are usually set at or very near the bottom of the aquifer and pumping levels closely correspond to this depth in times of peak pumpage.

Irrigation pumpage in 1961 had little effect on the reservoir, except in a small area of concentrated development in northeastern Mitchell County where a small cone of depression appears to have developed in the water table. However, mutual interference between wells is reported in widely scattered places, and irrigation wells pumping near livestock or domestic wells have often lowered the water level in the aquifer below the depth of the smaller wells. Prior to 1953, the municipal supply for Colorado City was from the Santa Rosa, and some industrial use of water also occurred in this area. Long-continued pumping of these municipal wells created cones of depression of considerable magnitude before pumping ceased from these wells in 1953. However, recent measurements indicate that water levels have recovered to their approximate original positions. Well development near the interface of the fresh and brackish water in the Santa Rosa aquifer in Mitchell and Scurry Counties may cause movement of water of poor quality into the areas productive of fresh water. This condition could possibly occur in the western part of Region I.

## Ground Water Available for Development

In the western part of Region I, ground water in the Santa Rosa aquifer is under artesian conditions. The amount of recharge to the aquifer and the quantity of water obtainable from storage are not known. There is probably a considerable amount of water available from artesian storage; however, it may not be economically feasible to recover much of this because of low well yields and deep pumping lifts. Some water should be available on a perennial basis depending on conditions of recharge and aquifer transmission capacity.

In the eastern part of Region I, the amount of water estimated to be available for development is on a perennial basis. Water-level data in Mitchell and Nolan Counties indicate that there has been a general rise in water levels in irrigation wells in the eastern part of the region since 1957; if annual pumpage from the aquifer since 1957 has not varied appreciably from the estimated 1960 pumpage of 37,000 acre-feet, it seems reasonable to assume that recharge to the aquifer is sufficient to sustain an annual pumpage of on the order of 30,000 to 40,000 acre-feet, assuming, of course, that the 1960 pumpage estimate is correct.

In addition to the availability of water from the Santa Rosa aquifer in areas where it produces water containing less than 3,000 to 4,000 ppm dissolved solids, large quantities of otherwise unusable water should be available from the Santa Rosa Formation for water-flooding and other industrial operations in the central areas of Region I. However, data are not available to evaluate the water-producing potential of the Santa Rosa Formation in these areas and determination of this is beyond the scope of the present reconnaissance study.

## Other Aquifers

### Chinle Formation

Sand and gravel in the Chinle Formation of the Dockum Group (Triassic) yield water to wells in parts of Scurry, Borden, Ector, Andrews, and Dawson Counties. Wells producing usable water from these deposits are generally on or very near the outcrop or subcrop areas.

Dissolved solids in water produced from 34 Chinle wells in Borden County range from 248 to 10,800 ppm.

About 58 irrigation wells in south-central Dawson and north-central Martin Counties pumped about 1,500 acre-feet of water from a sand member of the Chinle Formation in 1960. This producing section consists of about 30 feet of sand and gravel, and occurs at depths of about 230 to 260 feet below land surface. The pumpage from this aquifer is included with that for "other aquifers" of Region I in Table 3. Fresh-water-bearing sand and gravel in the Chinle are known to occur in numerous other areas in the High Plains and suspected to occur in others.

Sand and gravel of the Chinle Formation occur beneath all of the High Plains part of Region I, conforming somewhat to the dip and strike of the underlying Santa Rosa Formation. Subsequent investigations may reveal additional water supplies in Chinle deposits, particularly in water-short areas.

### Cretaceous Rocks (Outliers)

East of the High Plains escarpment in Region I, there are several isolated outliers, or erosional remnants, of Cretaceous strata which generally contain some water. The quantity of water available from an individual outlier depends largely upon the size of the outlier.

One outlier that is large enough to merit discussion in this report is in the northwestern corner of Scurry County where it encompasses an area of about 48 square miles and is partly buried beneath younger sediments. The areal extent of the saturated interval within the outlier is about 30 square miles. The Cretaceous section is about 170 feet thick, with basal sands of the Trinity Group having up to 40 feet of saturated thickness. Depths of water in wells tapping the Cretaceous sands of this outlier range from 46 to 132 feet. Thirteen irrigation wells and four municipal wells pumped approximately 310 and 10 acre-feet of water, respectively, during 1960. Well yields average only about 35 gpm. Water produced from this outlier is of uniformly good chemical quality. Dissolved solids range from 318 to 389 ppm as determined by analyses of three samples.

### Alluvium

Thin sand and gravel beds, believed to be river terrace deposits, in southwestern Scurry County supply limited amounts of potable water for domestic and livestock-watering purposes (grids 28-23 and 28-32). The water table in these sands and gravels is very near the land surface, creating numerous seep springs at the edges of the deposits. Evapotranspiration concentrates the dissolved solids in some of these spring areas, producing mineralized water and soils that reportedly contain large amounts of sulfate compounds. Analyses of two water samples, one collected from a spring issuing from sand below the base of alluvial deposits near Knapp, in Scurry County, and the other from a well completed in material believed to be terrace deposits of the Colorado River, about 5 miles southwest of Ira, also in Scurry County, indicated dissolved solids of 1,850 and 1,140 ppm, respectively.

Sand and gravel deposits within the Colorado River floodplain in Borden County (grids 28-21, -22, -29, and -30) supplied approximately 150 acre-feet of water through seven wells for refining of liquified petroleum products in 1960. These wells produced from zones having not more than 12 feet of saturated thickness. Overflow from the Colorado River and water from precipitation provide the necessary recharge for sustaining this operation. The chemical analysis of a sample of water from one of the wells indicated a dissolved-solids content of 654 ppm.

## Region II

One primary aquifer, the Edwards-Trinity (Plateau), and two secondary aquifers, the Ellenburger-San Saba and the Hickory, occur in Region II of the Colorado River basin. (See Figure 5, page 23.) The small portion of the Edwards-Trinity (Plateau) primary aquifer which extends northwesterly into the southern part of Region I is treated in the discussion of that region; that larger portion of the aquifer occurring in Region II will be discussed in this section of this report. Included for quantitative purposes with the Edwards-Trinity (Plateau) primary aquifer in this Region II discussion are fresh-water-bearing sands of Triassic age.

Other aquifers in Region II, those which are more limited in areal extent and have a limited potential for further development but which supply small to moderate quantities of ground water for municipal, industrial, irrigation, domestic, or livestock-watering purposes, are: alluvium, Permian rocks, Pennsylvanian rocks, the Welge Sandstone Member of the Wilberns Formation, Precambrian rocks, and the Trinity Group (North-Central Texas).

## Primary Aquifer

### Edwards-Trinity (Plateau) Aquifer

Although the Edwards-Trinity (Plateau) aquifer was discussed in Region I, the aquifer extends into Region II where it covers a larger area and attains a greater thickness. The Edwards-Trinity (Plateau) aquifer of both regions is a hydraulically connected, continuous unit but is separated principally for discussion of availability of water.

The Edwards-Trinity (Plateau) aquifer is so named because it may be composed of two different aquifers, water-bearing units of the Edwards and associated limestones, and sands of the Trinity Group. Because these units are so often concurrently present and because of the nature of the hydraulic relationship between them they are considered as a single aquifer for reconnaissance purposes.

The areal extent of the Edwards-Trinity (Plateau) aquifer in Region II is defined as the areally continuous Edwards and associated limestones and Trinity Group sands south of the Colorado River and west of Blanco County. In Blanco County and eastward, these rocks are capable of yielding water only to small water-supply systems. The Edwards-Trinity (Plateau) aquifer contains usable (containing less than 3,000 ppm dissolved solids) water throughout its defined areal extent except for isolated areas in Upton and Reagan Counties in the northwestern part of Region II.

#### Geologic Characteristics

The limestone part of the aquifer, usually referred to as the Edwards and associated limestones, consists of the Comanche Peak and Edwards Limestones and the Georgetown Limestone of the Washita Group. In Region II of the Colorado River basin, however, the zone of saturation probably does not extend as high in the stratigraphic section as the Georgetown. (In the following discussion the term "Edwards" implies the Edwards and associated limestones considered as a unit.) The Edwards consists of light-colored, hard to soft limestone and dolomite beds and often is fossiliferous. Well-developed solutional openings are common both above and within the zone of saturation. Thickness of the Edwards may exceed 500 feet in parts of the high plateau areas in the southern parts of the region where the Edwards is overlain by shale and limestone of the Washita Group. Where the Edwards is exposed at the surface in plateau terrain, it is characterized by numerous sinkholes, some of them scores of feet in diameter, through which surface water flows freely into the subsurface. These sinks serve, therefore, as recharge areas to the zone of saturation.

Sands of the Trinity Group, the Paluxy Sand and the Hensell Sand Member of the Travis Peak Formation, are not coexistent. The Paluxy occurs in the northwestern part of the region and the Hensell in the southeastern part. An intervening area is occupied by a buried ridge. The Paluxy where it exists occurs directly beneath the Edwards, but the Hensell is separated from the Edwards by the Glen Rose Formation and Walnut Clay. These features are diagrammatically illustrated on the geologic section of Figure 9 and by the contours on Plate 10.

The Paluxy Sand consists of fine-grained sand and consolidated sandstone with occasional beds of clay. The Paluxy attains a maximum thickness of more than 100 feet. In southern Reagan and Irion Counties, the Paluxy Sand is in direct contact with, and appears indistinguishable on logs from, the underlying Santa Rosa Formation. The two sand units in this area appear to behave as a single hydrologic unit of 200 to 300 feet thickness.

The Hensell Sand Member occurs in the southeastern part of Region II and consists of lenses of varicolored clay, silt, and coarse sand with occasional layers of conglomerate at the base. The physical composition of the Hensell is heterogeneous, and water-bearing sands usually comprise less than 50 percent of the total thickness, which is in places as much as 400 feet. The Hensell Sand Member grades both laterally and vertically into the Glen Rose Formation, which does not yield appreciable quantities of water. The Hensell in parts of Gillespie and Kimble Counties is in contact with water-bearing rocks of Cambrian and Ordovician age and is therefore hydraulically in connection with them. Both the Hensell Sand Member and the Paluxy Sand were deposited on an erosional surface of pre-Cretaceous rocks.

Sands of the Trinity Group, the Hensell Sand Member and the Paluxy Sand. occur mostly in the subsurface. Their outcrops are relatively small areas which flank the Edwards Plateau and occupy valleys of some streams which have eroded deeply enough into the Edwards Plateau to strip away the overlying limestones.

Edwards and Trinity rocks dip uniformly to the southeast at approximately 50 feet per mile.

## Occurrence and Movement of Ground Water

Ground water in the Edwards-Trinity (Plateau) aquifer occurs under both water-table and artesian conditions in Region II. In sands of the Trinity Group the water is under artesian conditions where the sands are completely saturated and are overlain by clay or nonporous limestone. Otherwise, water-table conditions prevail, generally in areas of outcrop and in areas of major pumpage. In the limestones, solution openings generally are continuous above and into the zone of saturation, and therefore water-table conditions generally prevail.

In the northwestern part of Region II, the Paluxy Sand is hydraulically in connection with the overlying Edwards; here the two units generally are under common hydrologic conditions and the limestones supply most of the sand's recharge regionally. In the southeastern part of the region, the Hensell Sand Member is separated from the Edwards by the Glen Rose Formation and the Walnut Clay, and therefore the Hensell Sand Member and the Edwards are under different hydrologic conditions.

Ground water in the Edwards-Trinity (Plateau) aquifer moves regionally from northwest to southeast, as shown on Plate 11. It moves locally from areas of recharge to surface drainage courses, where the ground water is discharged into and supports the base flow of streams. Generally, the altitude of the water table correlates with that of the surface topography.

## Recharge and Discharge

As previously indicated, direct recharge to the Edwards occurs in areas between streams, except in high plateau areas where the Edwards is overlain by relatively impermeable strata of the Washita Group. The Paluxy receives recharge mostly from the overlying Edwards which is hydraulically in connection with the Paluxy. The Hensell, which is not hydraulically in connection with the Edwards, probably receives most of its recharge from its outcrop area and smaller amounts from vertical percolation through overlying Glen Rose sediments. Some water in the Hensell possibly originates from underlying Cambrian and Ordovician aquifers where they are in contact with the Hensell.

Ground water is discharged naturally from the Edwards-Trinity (Plateau) aquifer through springs and seeps along drainage courses and by evapotranspiration along the periphery of the Edwards Plateau. Pumping from wells constitutes the artificial discharge from the Edwards-Trinity (Plateau) aquifer.

## Water Levels

Depths to water in the Edwards-Trinity (Plateau) aquifer in Region II range from the land surface in areas of natural discharge to more than 500 feet in the higher altitude areas of Upton, Reagan, and Irion Counties. Available data indicate that there is little regional fluctuation of water levels in the aquifer. Water-level fluctuations in response to pumpage and climatic conditions are recorded for areas of major development in southern Glasscock and northern Reagan Counties. As shown by hydrographs of irrigation wells on Figure 10, persistent yearly declines of 4 to 6 feet over the past 10 years have occurred in the St. Laurence irrigation area of Glasscock and Reagan Counties.

## Water-Bearing Characteristics

Solutional or cavernous openings developed in the Edwards limestones are similar to a system of conduits, and water is readily transmitted by them. Such a system, however, is not necessarily conducive to storage of large quantities of water, but locally it may contain moderate to large supplies. Because of the non-uniformity of the openings, a quantitative determination of storage and transmission capacities of the limestones is considered beyond the scope of this study.

Sands of the Hensell and Paluxy are generally fine grained and are therefore considerably less permeable than the overlying Edwards limestones, but the storage capacity of the sands is indicated to be regionally much greater than that of the limestones.

## Chemical Quality

Water from the Edwards-Trinity (Plateau) aquifer is of good quality throughout Region II except in its extreme northwestern areas in parts of Upton, Reagan,

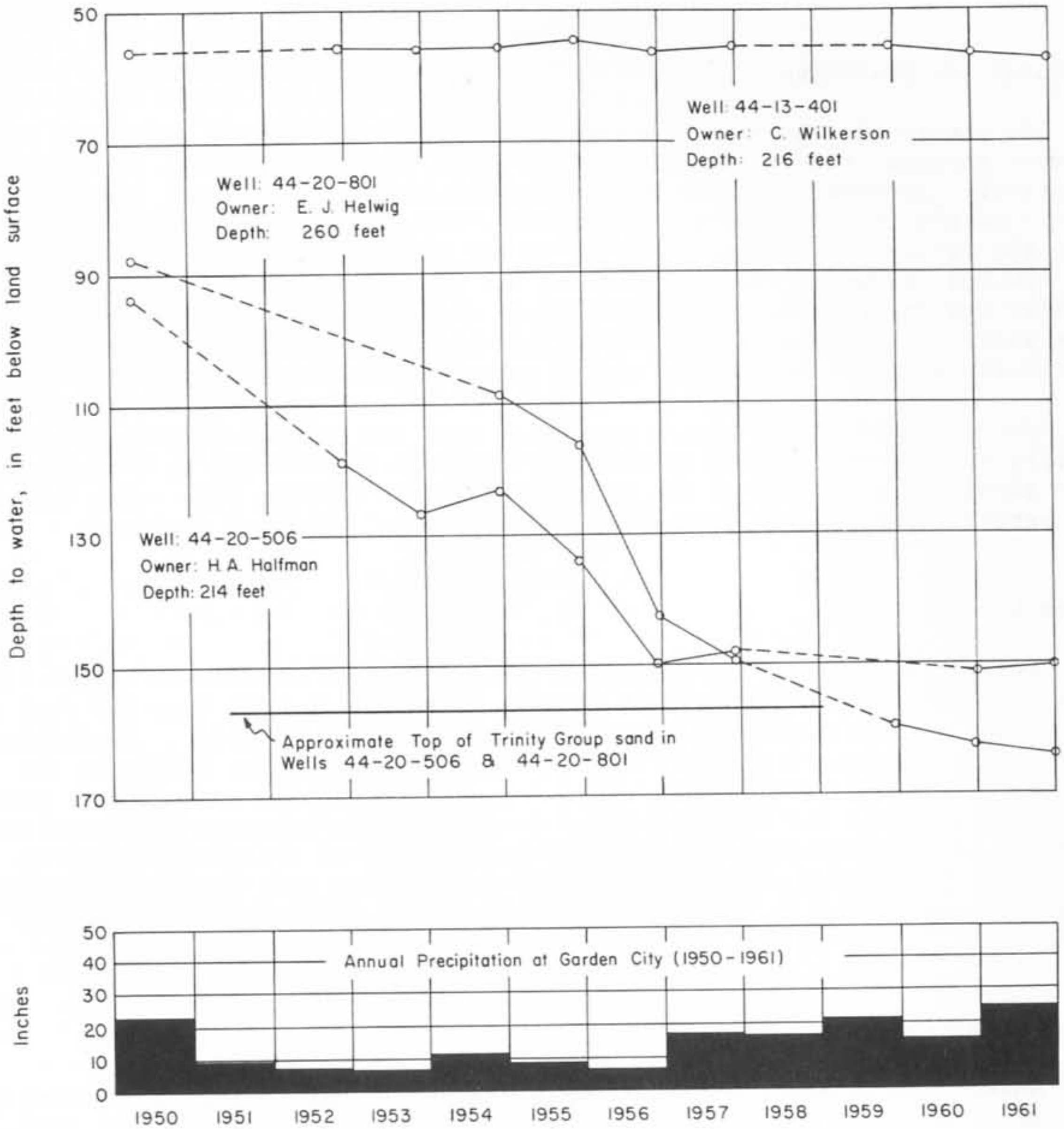



Figure 10

Hydrographs of Wells in Edwards-Trinity (Plateau) Aquifer, and Annual Precipitation at Garden City, Region II, Colorado River Basin

Texas Water Development Board in cooperation with the U. S. Geological Survey

Irion, and Glasscock Counties where the waters are too highly mineralized for industrial and municipal use but are generally suitable for irrigation. In these areas the available analyses show that dissolved solids generally range between 350 and 3,500 ppm, and in the more highly mineralized waters the principal objectionable properties are excessive hardness and high sulfate content. It is not certainly known to what extent contamination by oil-field brines is responsible for occurrences of highly mineralized waters, but it is of significant proportions in northeastern Reagan County.

In the remainder of the region, exclusive of the extreme northwestern areas, water although usually hard is uniformly of good quality, and dissolved-solids content generally ranges from 200 to 700 ppm. Chemical analyses of water from 30 selected wells producing from the Edwards-Trinity (Plateau) aquifer are given in Table 4 in order to illustrate the general quality of water in various parts of the aquifer. The location of wells from which the selected water samples were taken are plotted on Plate 10.

Future quality-of-water problems may develop in oil-producing areas where brines produced with oil are disposed into unlined surface pits. Improper disposal of wastes, along with inadequate protective measures, can result in the contamination of the fresh ground-water supply rendering it unfit for beneficial use. Widespread ground-water contamination has already resulted from surface disposal of brines in the Sprayberry oil field area of Reagan, Upton, and Glasscock Counties. Although surface-disposal practices have been discontinued in this area, some effect of the contamination will probably persist for many years.

### Utilization and Development

The Edwards-Trinity (Plateau) aquifer in Region II is a source of water supply for small towns and communities, for irrigation, and for petroleum industries, as well as for domestic and livestock-watering purposes. Major development of the aquifer is small and scattered throughout the region except for the St. Laurence irrigated area in Glasscock and Reagan Counties, where annual pumpage has been increasing since 1946, and an area of industrial pumpage in northeastern Upton County. The 1960 pumpage from the Edwards-Trinity (Plateau) aquifer in Region II amounted to approximately 27,000 acre-feet. Of this total, about 1,200 acre-feet was pumped for municipal use, 2,700 acre-feet for industrial use, and 23,000 acre-feet for irrigation. The estimate for 1960 irrigation pumpage in the northwestern part of Region II was determined by using the average well yield and average seasonal operating time and applying these to the total number of irrigation wells. Other irrigation pumpage for 1960 was estimated from 1958 pumpage figures obtained from Bulletin 6018 (Texas Board of Water Engineers, 1960b). Municipal, industrial, and irrigation pumpage from the Edwards-Trinity (Plateau) aquifer, by the major drainage subdivisions of Region II, is shown in Table 5. In addition, an undetermined amount of ground water is pumped for domestic and livestock-watering purposes.

Pumping rates of wells producing from the Edwards-Trinity (Plateau) aquifer in Region II range from a few gallons per minute to as much as a reported 1,800 gpm. Specific capacities of these wells generally range from 0.5 to 2 gpm per foot of drawdown, although some wells producing water from limestone cavities have specific capacities exceeding 200 gpm per foot of drawdown.

Table 4.--Representative chemical analyses of water from primary and secondary aquifers, Region II, Colorado River basin

(Analyses expressed in parts per million except specific conductance and pH.)

| Well | Owner | Depth of well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Cal-cium (Ca) | Magne-sium (Mg) | Sodium and po-tassium (Na + K) | Bicar-bonate ($HCO_3$) a/ | Sul-fate ($SO_4$) | Chlo-ride (Cl) | Fluo-ride (F) | Ni-trate ($NO_3$) | Dis-solved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Edwards-Trinity (Plateau) Aquifer | | | | | | | | | | |
| 28-62-101 | Mrs. Odom | 290 | 6-27-61 | 17 | -- | 99 | 11 | 99 | 219 | 55 | 184 | 1.0 | 9.4 | 583 | 292 | 1,040 | 6.8 |
| 42-41-802 | Mrs. Anna Ellis | 30(?) | 6-22-61 | 13 | -- | 84 | 24 | 11 | 274 | 19 | 20 | .3 | 72 | 402 | 308 | 639 | 7.2 |
| 43-02-702 | Union Texas Natural | 280-310 | 3- -61 | -- | 0 | 43 | 27 | 4 / -- | 222 | 18 | 20 | -- | -- | 335 | -- | -- | -- |
| 25-301 | Lula C. Harris, et al. | 156 | 3- 1-46 | 9 | 0 | 56 | 28 | 16 / -- | 270 | 22 | 18 | -- | -- | 418 | -- | -- | -- |
| 41-2 | Sugg Bros. | 110 | 7-22-40 | -- | -- | 92 | 22 | 4 | 348 | 10 | 20 | -- | <20 | 324 | 319 | -- | -- |
| 49-1 | Mrs. F. B. Carter | 240 | 8- 6-40 | -- | -- | 62 | 27 | 15 | 293 | 20 | 27 | .8 | <20 | 295 | 267 | -- | -- |
| 53-1 | T. D. and S. V. Easterwood | 60 | 5-18-50 | 23 | -- | 90 | 26 | 71 | 378 | 75 | 62 | -- | 14 | 554 | 332 | 917 | 7.9 |
| 44-05-5 | A. D. Neal | 195 | 3- 3-37 | -- | -- | 66 | 7 | 9 | 214 | < 10 | 28 | -- | -- | 215 | 194 | -- | -- |
| 14-201 | Steve Currie | 110 | 11- -43 | -- | -- | 144 | 53 | 164 | 376 | 358 | 173 | 1.7 | 7.4 | 1,160 | 578 | -- | -- |
| 26-101 | Ray Barrett, Jr. | 319 | 8-22-61 | 9.9 | -- | 120 | 44 | 155 | 235 | 508 | 49 | 2.4 | 24 | 1,030 | 480 | 1,450 | 6.9 |
| 28-706 | E. C. Nunn Estate | -- | 2-26-55 | -- | -- | 388 | 185 | 420 / -- | 227 | 1,800 | 412 | -- | -- | 3,432 | -- | -- | 7.1 |
| 28-901 | Reagan Co. WC&ID | -- | 1- -60 | 1.0 | < .05 | 45 | 30 | 14 / -- | 234 | 33 | 24 | 1.1 | 14.0 | 339 | 238 | 565 | -- |
| 39-3 | C. H. Sugg | 160 | 7- 8-40 | -- | -- | 60 | 48 | 9 | 329 | 20 | 32 | 1.9 | 34 | 366 | 350 | -- | -- |
| 43-203 | Stanley Turner | 194 | 8-30-61 | 12 | -- | 150 | 74 | 306 | 258 | 898 | 124 | 3.1 | 17 | 1,710 | 678 | 2,320 | 6.8 |
| 47-4 | Sawyer Land & Cattle | 265 | 5-27-40 | -- | -- | 70 | 42 | 161 | 293 | 217 | 160 | 2.1 | <20 | 796 | 346 | -- | -- |
| 52-101 | Atlantic Refining Co. | 485 | 7-29-60 | 10 | -- | 149 | 99 | 270 | 250 | 902 | 145 | 2.9 | 11 | 1,710 | 779 | 2,300 | 7.4 |
| 54-702 | Barnhart Hydrocarbons | 632 | 3-31-60 | 7 | -- | 94 | 83 | 423 | 373 | 760 | 286 | -- | Trace | 2,026 | 576 | 2,700 | 7.8 |
| 55-501 | Ted Russell | 240 | 7-17-53 | 28 | .18 | 115 | 8 | 35 / -- | 354 | 39 | 39 | .4 | 11 | 464 | 320 | -- | 7.5 |
| 55-12-101 | City of Eldorado | 361 | 9-21-48 | 14 | .65 | 47 | 24 | 15 / 2.8 | 212 | 27 | 26 | 2.2 | 8.5 | 282 | 216 | 498 | 7.5 |
| 31-401 | Philip Jacoby | 225 | 5-10-61 | 16 | -- | 54 | 31 | 13 | 281 | 22 | 24 | .5 | 1.2 | 300 | 262 | 534 | 7.0 |
| 54-101 | J. D. Wallace | 403 | 4-25-55 | 14 | -- | 54 | 22 | 11 | 270 | 6.1 | 12 | .6 | 3.2 | 256 | 225 | 457 | 7.9 |
| 63-701 | City of Rocksprings | 563 | 3-16-54 | 14 | .01 | 44 | 18 | 11 / .7 | 210 | 6.9 | 16 | .3 | 2.0 | 216 | 184 | 398 | 8.0 |
| 56-01-901 | Mrs. F. T. Neal | 60+ | 7-27-60 | 14 | -- | 64 | 21 | 19 | 294 | 10 | 20 | .4 | 7.9 | 299 | 246 | 520 | 6.9 |
| 11-601 | John L. Royal | 128 | 6-14-61 | 18 | -- | 46 | 28 | 29 | 270 | 16 | 37 | .5 | 1.5 | 298 | 230 | 543 | 7.3 |
| 38-401 | Sam Honig | 125 | 5-31-61 | 18 | -- | 68 | 42 | 35 | 346 | 33 | 66 | .7 | 6.3 | 440 | 342 | 785 | 7.0 |
| 43-701 | Clarence Hyde | 421 | 6-29-61 | 14 | -- | 39 | 26 | 13 | 228 | 12 | 21 | .4 | 3.2 | 231 | 204 | 430 | 7.4 |

See footnotes at end of table.

Table 4.--Representative chemical analyses of water from primary and secondary aquifers, Region II, Colorado River basin--Continued

| Well | Owner | Depth of well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 56-46-601 | Max Lang | 35 | 11-30-60 | 16 | -- | 119 | 25 | 38 | 340 | 29 | 74 | 0.2 | 86 | 594 | 400 | 974 | 6.9 |
| 57-41-901 | City of Fredericksburg | 275 | 12- 1-60 | 12 | -- | 62 | 39 | 18 | 342 | 20 | 34 | .3 | 3.8 | 357 | 315 | 657 | 7.0 |
| 43-5 | William Schleider | 77 | 4-17-36 | -- | -- | 108 | 97 | -- | 560 | -- | 108 | -- | -- | 593 | 667 | -- | -- |
| 51-9 | Albert Wilke | 230 | 3-18-36 | -- | -- | 27 | 104 | 123 | 256 | 455 | 58 | -- | -- | 895 | 498 | -- | -- |
| | **Ellenburger-San Saba Aquifer** | | | | | | | | | | | | | | | | |
| 41-17-4 | A. C. Snyder | 2,402 | -- | -- | -- | 196 | 49 | 4,905 | 384 | 14 | 7,820 | -- | -- | 13,178 | 1,041 | -- | -- |
| 33-601 | S. H. Reeves | 1,100 | 11-28-60 | 14 | -- | 18 | 6.9 | 1,080 | 404 | 7.0 | 1,470 | 7.2 | 0.0 | 2,800 | 74 | 5,080 | 7.3 |
| 41-2 | J. M. Hatherly | 1,888 | 10-13-38 | -- | -- | 22 | 5 | 863 | 451 | 4 | 1,100 | 9.0 | -- | 2,225 | 73 | -- | -- |
| 401 | T. K. Adams | 755 | 7-22-47 | 11 | 0.25 | 106 | 23 | 12 4.2 | 420 | 11 | 22 | .4 | 3.5 | 400 | 359 | 688 | 7.3 |
| 51-6 | Tom Grozier | 116 | 2-11-39 | -- | -- | 74 | 34 | 10 | 366 | 16 | 22 | -- | -- | 336 | -- | -- | -- |
| 52-303 | J. L. Buttrill | 420 | 4- 5-49 | 30 | 0 | 10 | 7.6 | 497 2.8 | 550 | 113 | 401 | 1.6 | 1.8 | 1,330 | 56 | 2,250 | 8.6 |
| 58-601 | R. N. Manley | 240 | 9-10-38 | -- | -- | 95 | 49 | 2.2 | 500 | 8 | 14 | -- | 6.9 | 427 | 438 | -- | -- |
| 61-4 | T. S. Aylor | 163 | 3- 6-39 | -- | -- | 154 | 33 | 10 | 531 | 30 | 30 | -- | 41 | 559 | 520 | -- | -- |
| 42-31-401 | R. M. Vaughn | 2,180 | 11-16-60 | 16 | -- | 40 | 14 | 1,820 | 448 | .8 | 2,650 | 6.0 | -- | 4,770 | 158 | 8,430 | 7.7 |
| 38-601 | W. N. White | 1,600 | 7-26-51 | 15 | -- | 28 | 17 | 278 | 346 | 64 | 280 | -- | .2 | 871 | 140 | 1,600 | 8.2 |
| 42-601 | Carlos E. Jones | 3,418 | 12-11-57 | -- | 2 | 36 | 15 | 1,836 | 542 | 48 | 2,590 | -- | -- | 4,800 | -- | -- | 6.8 |
| 56-801 | J. W. Gibbons | 452 | 11-16-38 | -- | -- | 74 | 36 | 7.2 | 358 | 6 | 7.0 | -- | 15 | 339 | 306 | -- | -- |
| 62-7 | T. Gray | 625 | 6-19-58 | 16 | -- | 100 | 42 | 27 | 424 | 43 | 47 | .5 | 26 | 556 | 422 | 899 | 7.1 |
| 56-13-1 | Alf Reeves | 250 | 11-29-39 | -- | -- | 88 | 39 | 89 | 281 | 112 | 160 | -- | -- | 626 | 379 | -- | -- |
| 29-5 | Marvin Hoerster | 500 | 2- 7-40 | -- | -- | 72 | 21 | 25 | 268 | 28 | 52 | -- | -- | 330 | 268 | -- | -- |
| 57-02-302 | C. E. Yoakum | Spring | 12-15-54 | 93 | .00 | 82 | 45 | 5.9 2.8 | 464 | 8.5 | 10 | .2 | 7.5 | 407 | 390 | 707 | 7.4 |
| 15-701 | City of Burnet | 168 | 8- 3-61 | 11 | -- | 96 | 31 | 23 | 410 | 16 | 34 | .3 | 20 | 436 | 367 | 754 | 7.0 |
| 23-401 | Houston Clinton | 240 | 10- 1-53 | 13 | -- | 82 | 44 | 17 | 449 | 15 | 25 | .4 | 5.6 | 428 | 386 | 764 | 7.6 |
| 38-501 | Oscar Robinson | 171 | 8-10-38 | -- | -- | 28 | 29 | 14 | 189 | 21 | 29 | .2 | -- | 214 | 188 | -- | -- |
| 45-901 | City of Johnson City | 252 | 11-14-60 | 14 | -- | 87 | 43 | 23 | 384 | 69 | 32 | .6 | 13 | 471 | 394 | 798 | 6.9 |
| 50-101 | City of Fredericksburg | 260 | 8-15-60 | 16 | -- | 78 | 42 | 49 | 354 | 35 | 96 | .4 | 13 | 537 | 367 | 901 | 6.8 |
| 53-501 | W. D. Glasscock | 1,005 | 8- 6-41 | -- | -- | 379 | 138 | 78 | 336 | 1,312 | 23 | 3.3 | 1.0 | 2,090 | 1,515 | -- | -- |

See footnotes at end of table.

Table 4.--Representative chemical analyses of water from primary and secondary aquifers, Region II, Colorado River basin--Continued

| Well | Owner | Depth of well (feet) | Date of collection | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Hickory Aquifer | | | | | | | | | |
| 41-59-803 | Floyd McRorey | 675 | 1-14-59 | 12 | -- | 67 | 22 | 18 9.8 | 318 | 19 | 18 | 0.8 | 0 | 323 | 258 | 576 | 7.4 |
| 42-46-301 | M. D. Rice | 2,580 | 11-25-58 | 14 | -- | 12 | 6.5 | 263 | 329 | 54 | 215 | -- | .5 | 738 | 56 | 1,300 | 8.2 |
| 50-103 | City of Eden | 4,150 | 6- 3-54 | 23 | 0.08 | 6 | 2.2 | 408 .21 | 439 | 22 | 400 | 2.0 | .8 | 1,100 | 24 | 1,960 | 8.1 |
| 52-401 | City of Melvin | 2,800 | 3- -52 | 11 | .68 | 63 | 24 | 71 | 323 | 53 | 64 | .6 | -- | 426 | 253 | -- | 7.7 |
| 54-702 | City of Brady | 2,114 | 6-20-58 | 15 | -- | 54 | 40 | 36 | 367 | 49 | 16 | .8 | .2 | 382 | 299 | 671 | 7.3 |
| 56-07-207 | J. W. Behrens | 125 | 77-10-58 | 28 | -- | 51 | 9.4 | 34 3.3 | 160 | 27 | 46 | 1.0 | 27 | 317 | 166 | 512 | 6.6 |
| 14-101 | Werner Schmidt | 385 | 1-23-59 | 16 | -- | 77 | 62 | 49 | 474 | 80 | 54 | .7 | 5.7 | 564 | 447 | 991 | 7.2 |
| 23-102 | City of Mason | 170 | 1- -60 | -- | .08 | 56 | 28 | 6 | 262 | 16 | 21 | .5 | 3.9 | 297 | 215 | 495 | 7.4 |
| 32-4 | Milton Brandenberger | 264 | 1- 4-40 | -- | -- | 68 | 21 | 66 | 390 | 17 | 45 | .4 | -- | 409 | 258 | -- | -- |
| 57-01-501 | W. H. Taylor | 105 | 1-14-59 | 20 | -- | 55 | 4.4 | 7.1 .8 | 176 | 6.8 | 7.5 | .5 | 12 | 207 | 155 | 339 | 7.9 |
| 02-701 | R. G. Kuykendall | 75 | 1-20-59 | 14 | -- | 74 | 26 | 19 | 333 | 16 | 24 | .5 | 8.8 | 340 | 292 | 618 | 7.4 |
| 03-301 | Ide Tinny | 165 | 1-14-59 | 12 | -- | 66 | 15 | 18 | 245 | 20 | 29 | 1.0 | 0 | 271 | 226 | 509 | 7.9 |

a/ Includes the equivalent of any carbonate ($CO_3$) present.
b/ Some analyses include the sum of the total constituents; others, about half the bicarbonates.

Table 5.--1960 Ground-water pumpage from aquifers in Region II, Colorado River basin

(Pumpage, some of which is estimated, is in acre-feet, and should be considered accurate to no more than two significant figures. Municipal pumpage includes water supplied by privately-owned systems. Irrigation pumpage partly for 1958 (Texas Board of Water Engineers, 1960b).)

| Use | 1960 Pumpage, by major drainage subdivision | | | | | | | | | | | | | | | | | | | | Total 1960 pumpage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 21 | 22 | 23 | 24 | 27 | 31 | 34 | 40 | 41 | 43 | 44 | 46 | 47 | 48 | 50 | 52 | 54 | 56 | 57 | 59 | |
| **Edwards-Trinity (Plateau) Aquifer** | | | | | | | | | | | | | | | | | | | | | |
| Municipal | -- | -- | -- | 407 | 206 | 34 | -- | -- | -- | -- | -- | 162 | -- | -- | 184 | -- | -- | -- | 201 | -- | 1,194 |
| Industrial | 231 | -- | -- | 2,236 | 207 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 2,674 |
| Irrigation | -- | -- | -- | 15,511 | 1,541 | 4,734 | -- | -- | -- | 361 | 50 | -- | -- | -- | -- | -- | -- | 80 | 590 | -- | 22,867 |
| Subtotal | 231 | -- | -- | 18,154 | 1,954 | 4,768 | -- | -- | -- | 361 | 50 | 162 | -- | -- | 184 | -- | -- | 80 | 791 | -- | 26,735 |
| **Santa Rosa Aquifer** | | | | | | | | | | | | | | | | | | | | | |
| Irrigation | 269 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 269 |
| Subtotal | 269 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 269 |
| **Ellenburger-San Saba Aquifer** | | | | | | | | | | | | | | | | | | | | | |
| Municipal | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 602 | 201 | 803 |
| Irrigation | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 60 | -- | -- | -- | -- | -- | 366 | 60 | 486 |
| Subtotal | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 60 | -- | -- | -- | -- | -- | 968 | 261 | 1,289 |
| **Hickory Aquifer** | | | | | | | | | | | | | | | | | | | | | |
| Municipal | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 95 | 1,710 | -- | -- | -- | 2,128 | -- | -- | -- | 3,933 |
| Industrial | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 274 | -- | -- | -- | -- | -- | -- | -- | -- | -- | 274 |
| Irrigation | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 3,129 | -- | -- | 115 | -- | 748 | 1,964 | -- | -- | -- | 5,956 |
| Subtotal | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 3,403 | 95 | 1,710 | 115 | -- | 748 | 4,092 | -- | -- | -- | 10,163 |
| **Other Aquifers*** | | | | | | | | | | | | | | | | | | | | | |
| Municipal | -- | -- | -- | -- | 59 | 369 | 60 | 124 | 343 | -- | 264 | -- | 359 | 94 | 966 | -- | -- | -- | -- | 126 | 2,764 |
| Irrigation | -- | -- | 163 | -- | 123 | 2,160 | 5,229 | -- | -- | 50 | -- | -- | 590 | -- | -- | -- | -- | -- | 60 | 75 | 8,450 |
| Subtotal | -- | -- | 163 | -- | 182 | 2,529 | 5,289 | 124 | 343 | 50 | 264 | -- | 949 | 94 | 966 | -- | -- | -- | 60 | 201 | 11,214 |
| **Summary of Pumpage in Region II** | | | | | | | | | | | | | | | | | | | | | |
| Municipal | -- | -- | -- | 407 | 265 | 403 | 60 | 124 | 343 | -- | 264 | 257 | 2,069 | 94 | 1,150 | -- | 2,128 | -- | 803 | 327 | 8,694 |
| Industrial | 231 | -- | -- | 2,236 | 207 | -- | -- | -- | -- | -- | 274 | -- | -- | -- | -- | -- | -- | -- | -- | -- | 2,948 |
| Irrigation | 269 | -- | 163 | 15,511 | 1,664 | 6,894 | 5,229 | -- | -- | 411 | 3,179 | -- | 650 | 115 | -- | 748 | 1,964 | 80 | 1,016 | 135 | 38,028 |
| Total | 500 | -- | 163 | 18,154 | 2,136 | 7,297 | 5,289 | 124 | 343 | 411 | 3,717 | 257 | 2,719 | 209 | 1,150 | 748 | 4,092 | 80 | 1,819 | 462 | 49,670 |

* Precambrian rocks, Welge Sandstone Member of the Wilberns Formation, Pennsylvanian rocks, Permian rocks, Trinity Group (North-Central Texas), and alluvium.

Because the Edwards and Trinity rocks usually are well consolidated, wells producing from them are generally uncased except through the upper few feet of surface soil. However, casing is necessary for Hensell wells and for some Paluxy wells to prevent caving. In Hensell wells, casing is set to the depth of the hole and is slotted or perforated at producing intervals. Less commonly, screens and liners are used and producing zones are underreamed and gravel packed.

Most major wells producing from the Edwards-Trinity (Plateau) aquifer are equipped with turbine pumps that are driven by 3- to 25-horsepower electric motors or 6- to 8-cylinder combustion engines which generally use natural gas for fuel. A number of wells are equipped with electric-powered submersible pumps.

Problems resulting from pumpage are of two kinds: (1) drawing saline waters from contaminated areas into an expanding cone of depression, and (2) lowering of water levels to such an extent that unwatering of the aquifer becomes likely. As of 1960, these problems may have occurred only in the northwestern part of Region II, in an area embracing parts of Reagan, Upton, and Glasscock Counties. This area contains the Big Lake municipal well field of Reagan County and the St. Laurence irrigation area of Glasscock and Reagan Counties. The occurrence of highly mineralized water in and near these areas indicates the possibility that water of poorer quality may be produced from these wells in the future. Increasing pumpage of water from irrigation wells in the St. Laurence area since 1946 has caused water levels in some wells to decline more than 70 feet below the pre-irrigation static levels. Hydrographs on Figure 10 show the decline rates of water levels since 1950 with the approximate base of the limestone imposed on them. Plate 11, a contour map of water levels in Region II, shows that water-level depressions of significant size have been caused by pumpage in the St. Laurence area and in the Big Lake municipal well field. In general, recharge to the Edwards-Trinity (Plateau) aquifer is probably small, and only a small amount of recharge can be captured by any particular well field. Therefore, recharge is inadequate to sustain a sizeable concentration of wells in most areas of the northwestern part of Region II, and pumpage is largely derived from storage of water in the sand and limestones.

The principal qualifications on concentrated development in Region II are that the aquifer can be locally unwatered and that oil-field brine already introduced into the subsurface may be encountered in pumped wells in oil-producing areas. However, the long-range threat of contamination will be substantially reduced with the abolition of surface-pit disposal practices.

## Ground Water Available for Development

Because of differences in geologic and hydrologic conditions encountered throughout the areal extent of the Edwards-Trinity (Plateau) aquifer in Region II, availability of ground water for future development has been estimated separately for the parts of the aquifer that are, respectively, north and south of the Middle Concho River.

North of the Middle Concho River, most of the aquifer's water occurs in sands of the Trinity Group and associated Triassic sands. In parts of the area where appreciable development has occurred (in southern Glasscock, northern

Reagan, and northeastern Upton Counties) the rates of withdrawal of water from the aquifer exceed the available recharge. In these parts of the area north of the Middle Concho River, it is estimated that 10,000,000 to 15,000,000 acre-feet of water is stored in the Trinity sands. This estimate is based on an average saturated sand thickness of 100 feet and an assumed specific yield of 0.15. Of the total amount of water in storage, probably 5,000,000 to 10,000,000 acre-feet may be economically withdrawn. In addition, an undetermined but relatively small amount of recharge is available for development. For the remaining portions of the area north of the Middle Concho River, development of the ground water in 1960 was of minor extent, but it is believed that there is at least as much water in storage as in the developed parts of the area, perhaps even more; an undetermined amount of recharge is also available. Therefore, it is estimated that for the Edwards-Trinity (Plateau) aquifer north of the Middle Concho River in Region II, 10,000,000 to 20,000,000 acre-feet of stored water and an additional amount of recharge are available for future development. Principal qualifications on concentrated development of water in any relatively small area in this part of Region II are that, in effect, water will be "mined" and that the aquifer will probably be locally depleted in the future.

South of the Middle Concho River, the Paluxy Sand becomes thinner and eventually disappears, and saturation is principally in the limestones. Because of the nature of cavernous openings in these limestones, the amount of water in storage cannot be accurately determined. Therefore, consideration of ground water available for development must be approached on the perennial-yield basis, involving determination of annual recharge as indicated by measurements of natural discharge. On the basis of flow measurements of the Llano River, it was determined that about 6 percent of the average annual precipitation recharged the Edwards in its outcrop area in the South Llano River drainage basin (Long, 1962, p. 25). Assuming that from 4 to 6 percent of the average annual precipitation infiltrates into the Edwards throughout its extent in Region II south of the Middle Concho River, it is estimated that 300,000 to 400,000 acre-feet of ground water per year moves through the Edwards in this area. It appears that at least 50 percent of this amount is available on a perennial basis for development by a system of wells spaced over the area. Such large-scale development of the Edwards would, of course, reduce significantly the base flow of major streams.

As discussed in a previous section, the Hensell is also water bearing south of the Middle Concho River. However, because of lack of available data, availability of water from the Hensell sands is not estimated. Indications are that its yield is small, perhaps less than 50,000 acre-feet per year. In view of the low order of magnitude of water that might be available from the Hensell as compared with the amount available from the Edwards, the estimated 150,000 to 200,000 acre-feet of ground water available from the Edwards on a perennial basis appears to be within the order of magnitude of ground water available from the Edwards-Trinity (Plateau) aquifer.

## Secondary Aquifers

### Ellenburger-San Saba Aquifer

The Ellenburger Group, of Ordovician age, and the San Saba Member of the Wilberns Formation, of Upper Cambrian age, are two separate geologic units, but because of the difficulty in distinguishing between them, especially in the subsurface, they are considered in this report as one aquifer.

### Geologic Characteristics

The Ellenburger Group is divided into three formations which are, from youngest to oldest, the Honeycut, Gorman, and Tanyard Formations. The Tanyard Formation is further subdivided into two members, which are, also from youngest to oldest, the Staendebach Member and the Threadgill Member (Table 1).

Ellenburger rocks are principally limestone and dolomite, and for the most part are non-glauconitic. Limestone of the Ellenburger Group is generally fine grained and colored light gray. Dolomite of the Ellenburger Group ranges from very fine grained to coarse grained and is often colored brightly in the upper part of the group. San Saba rocks, predominantly limestone to the northwest of the Llano uplift, grade to dolomite to the southeast. Limestone of the San Saba is usually medium grained, and dolomite is typically finer grained than that of the overlying Ellenburger rocks. Also, by comparison, San Saba rocks are generally darker colored than Ellenburger rocks and are commonly glauconitic.

Plate 12 shows the approximate altitude of the top of the Ellenburger-San Saba aquifer where it is believed to contain water having less than 3,000 ppm dissolved solids. As shown by the contours on Plate 12, the Ellenburger-San Saba dips away from the Llano uplift on all sides and is absent over much of the uplift because of erosion. Also, because of intense faulting, structural conditions are very complex. Basic data which would indicate the extent of the fresh-water-bearing (containing water having less than 3,000 ppm dissolved solids) portion of the Ellenburger-San Saba aquifer are scarce, available only north, west, and southeast of the Llano uplift, but on the basis of available chemical analyses the aquifer is generally presumed to extend less than 20 miles from the outcrop on all sides of the uplift.

Except where truncated below the Cretaceous rocks or at the surface, the Ellenburger-San Saba is known to vary in thickness from less than 1,000 feet northwest of the Llano uplift to more than 2,000 feet southeast of the uplift.

The depth to the top of the aquifer where it contains fresh water varies from the land surface in its outcrop area to more than 2,000 feet below the land surface in northern McCulloch County.

### Occurrence and Movement of Ground Water

Water in the Ellenburger-San Saba aquifer occurs in vugular, or cavernous, zones which are common throughout the aquifer, and in fractures and joints that in places are solution-enlarged.

Water can be produced from any unit in the aquifer; however, dolomitic portions of the Staendebach Member indicate greatest favorability for supplying water to wells (Cloud and Barnes, 1946, p. 127). Water-bearing zones also are formed in dolomitic portions of the San Saba Member. Water-bearing zones within the Ellenburger-San Saba aquifer generally are not horizontally continuous over large areas as is the case in most sand aquifers. Water-bearing zones are, with probably a few exceptions, under artesian pressure.

The direction in which the water moves through the Ellenburger-San Saba aquifer in Region II cannot accurately be determined because of lack of data. The general direction of movement is believed to be away from the Llano uplift. At or near the outcrop, water entering the aquifer from the land surface moves downward to the water-bearing zones, and then more or less horizontally toward points of discharge.

## Recharge and Discharge

Recharge to the Ellenburger-San Saba aquifer in Region II is derived from precipitation on upland areas of outcrop where permeable zones are exposed at the land surface and from streams where they flow over permeable rocks of the aquifer. Because San Saba and Ellenburger outcrops generally form rugged terrain with thin stony soils, surface runoff is greatly favored over infiltration. Water may also enter the aquifer in the subsurface through fault zones and from water-bearing units juxtaposed against the Ellenburger-San Saba by faulting. Significant recharge probably occurs where the aquifer is overlain by sands of the Trinity Group and alluvium.

Ground Water is discharged naturally from the Ellenburger-San Saba aquifer at springs along drainage courses, but some of the water discharged at the higher elevations may re-enter the aquifer in a lower zone. Base flows of many of the streams in the Llano uplift region are supported sustantially by ground-water discharge from the Ellenburger-San Saba aquifer. Discharge also occurs in the subsurface by leakage into other rock units. Flowing and pumping wells constitute the artificial discharge from the Ellenburger-San Saba aquifer. The pumping wells are scattered throughout the area, whereas flowing wells are usually in stream valleys, where the altitude of the land surface is lower than the hydrostatic head of the aquifer.

## Water Levels

Depths to water in the Ellenburger-San Saba aquifer in Region II vary considerably and depend somewhat on the altitude of the land surface at a particular site. Water levels in wells in the lower stream valleys generally are much closer to the land surface than those in wells in upland areas. In some topographically low areas wells flow naturally. Fluctuations of water levels result mainly from climatic variations. Water-level variations exceeding 40 feet over a 7-year period have been recorded in upland areas and reflect changes in aquifer storage during dry and wet years. Significant local changes in water levels due to pumping do not occur at the 1960 level of development.

## Water-Bearing Characteristics

In the Ellenburger-San Saba aquifer in Region II, water occurs in solution openings. Because of variations in the size of these openings and the degree of connection between them, storage and transmission capabilities of the aquifer cannot be realistically evaluated. Where solution openings are extensively developed, large well yields are common. However, aquifer properties can change markedly over short horizontal distances.

## Chemical Quality

Water from the Ellenburger-San Saba aquifer in Region II usually is of good quality, although very hard. Representative chemical analyses of water from selected wells producing from the Ellenburger-San Saba aquifer are presented in Table 4, and sites from which these samples were collected are shown on Plate 12. The dissolved-solids content of water in the aquifer generally is less than 1,000 ppm. Quality of water deteriorates rapidly away from outcrop areas, and at distances greater than 20 miles downdip from the outcrop, water is generally unsuitable for most uses. Chemical constituents in water from the Ellenburger-San Saba aquifer result from minerals dissolved not only from Ellenburger-San Saba rocks but also from rocks overlying them. To the northwest, increasing mineralization is due to sodium and chloride, and to the southeast, to calcium and sulfate.

Excessive hardness, which is common in waters of the Ellenburger-San Saba aquifer in Region II, can be reduced by application of commercial softening processes. One municipal-supply system (in 1960) supplies water that is treated for hardness.

## Utilization and Development

The Ellenburger-San Saba aquifer in Region II is a source of water for irrigation and for small towns and communities, as well as for domestic and livestock-watering purposes. The development of this aquifer is small and occurs mostly in and very near its outcrop.

Data on the history of development are not available; however, it is believed that pumpage has increased gradually over the past years and that maximum pumpage occurred during the drought years of the middle 1950's. The total pumpage in 1960 from major wells completed in the Ellenburger-San Saba aquifer in Region II is estimated to be about 1,300 acre-feet. Of this, about 800 acre-feet was pumped for municipal use, and about 490 acre-feet for irrigation. The estimate for 1960 irrigation pumpage is based on 1958 pumpage figures obtained from Bulletin 6018 (Texas Board of Water Engineers, 1960b). Pumpage from the Ellenburger-San Saba aquifer for 1960 is presented, by major drainage subdivisions, in Table 5.

The yields and specific capacities of wells producing from the Ellenburger-San Saba aquifer in Region II vary greatly from one well to another, depending on the aquifer properties at the particular well site. Although some wells are reported to yield more than 1,000 gpm, most wells yield less than 500 gpm. Specific capacities vary similarly. A specific capacity as high as 75 gpm per foot of drawdown has been computed from measurements at a well pumping 440 gpm, and specific capacities of approximately 50 gpm per foot of drawdown have been reported by a drilling contractor. However, such large specific capacities should be expected only where wells penetrate large cavities.

Major wells are completed with only a short length of surface casing set through surface soils to bedrock. Shaft-driven turbine pumps are used on major wells. Most wells are powered by electricity, although some irrigation wells use butane, gasoline, or diesel fuel to drive internal combustion engines.

### Ground Water Available for Development

Because of complicated geologic and hydraulic conditions, the amount of ground water available for development from the Ellenburger-San Saba aquifer in Region II can be only roughly estimated.

On the basis of flow measurements of streams passing through Ellenburger-San Saba outcrops, it is estimated that 20,000 acre-feet of water per year is discharged from the Ellenburger-San Saba aquifer in its outcrop areas. It is, therefore, believed that the aquifer is potentially capable of yielding on a perennial basis at least 20,000 acre-feet per year and probably more. However, it should be realized that because of the complex and intricate pattern of water-bearing zones in the Ellenburger-San Saba aquifer, yields of wells vary markedly. In order to develop large water supplies, a test-drilling program may be necessary.

## Hickory Aquifer

In this report, the Hickory aquifer is defined as a hydrologic unit consisting principally of the Hickory Sandstone Member of the Riley Formation (of Upper Cambrian age), but may include other stratigraphic units of Cambrian age that are hydraulically in connection with the Hickory.

### Geologic Characteristics

The Hickory Sandstone Member crops out intermittently around the periphery of the Precambrian core of the Llano uplift in the Central Mineral Region, as shown on the geologic map, Plate 2. In some areas adjacent to the core of the Llano uplift, Hickory outcrops are absent due to faulting or because of overlap by Cretaceous sediments.

As illustrated on the geologic section, Plate 4, the Hickory Sandstone Member and other Paleozoic rocks dip away from the Llano uplift in all directions and are cut by numerous faults. The average dip of the Hickory Sandstone Member is approximately 100 feet per mile. However, abrupt changes in dip may occur locally near faults.

The Hickory Sandstone Member is principally a tan to maroon, cross-bedded sandstone, medium- to fine-grained, and contains shale beds which become more numerous toward the top of the Member. The Hickory Sandstone Member was deposited upon a very uneven Precambrian topography, and its thickness varies considerably over short distances. However, average thicknesses of the Hickory Sandstone Member do not change appreciably over large areas. The average thickness of the Hickory aquifer is on the order of 400 feet, but only 50 to 75 percent of the total thickness can be depended upon to be water bearing.

The Hickory Sandstone Member grades upward and laterally into the Cap Mountain Limestone Member. In outcrop areas the boundary separating these two members of the Riley Formation is conventionally picked at a topographical and vegetational break, because the Hickory Sandstone Member is easily eroded to form gentle, sandy slopes which support deciduous trees, whereas the overlying Cap Mountain Limestone Member forms steeper and more resistant slopes or ridges covered with Cedar. In the subsurface, the Hickory Sandstone Member is distinguished by the absence or near absence of carbonate and glauconite.

North and west from the Llano uplift, the Cap Mountain Limestone Member thins and disappears, and the Hickory Sandstone Member is in contact with overlying Cambrian sandstones.

### Occurrence and Movement of Ground Water

Although the Hickory Sandstone Member crops out intermittently around the Llano uplift, its distinction as an important aquifer is considered only north and west of the uplift. However, the Hickory Sandstone Member yields water to small-diameter wells in other areas of its occurrence. Plate 13 shows the extent, configuration, and altitude on the top of the Hickory aquifer as considered in this report. The extent of the Hickory aquifer is not definitely known, but on the basis of chemical analyses of water from wells in Concho County, it is presumed to be at least 45 miles outward from the outcrop north and west of the Llano uplift.

The lower part of the Hickory aquifer yields water more readily than the upper part. Water-table conditions generally occur in outcrop areas; however, artesian conditions probably exist in individual sands where water in them is confined by overlying shale beds. All of the Hickory aquifer is under artesian conditions downdip, where both the Hickory and the Cap Mountain are overlain by other rocks.

Direction of water movement varies with geologic and topographic conditions. In outcrop areas, the configuration of the water table generally conforms to the contour of the land surface, and ground water moves toward the center of the Llano uplift. Downdip, water moves generally in the direction of dip and also laterally.

### Recharge and Discharge

The Hickory aquifer is recharged partly by precipitation which falls on the outcrop and which is readily absorbed by thick sandy soils. Because of a system of vertical fractures developed in the overlying Cap Mountain Limestone Member where it crops out, it is believed that water also enters the Hickory aquifer from Cap Mountain Limestone outcrops.

Natural discharge of ground water from the Hickory aquifer in outcrop areas is through seeps along surface drainage courses. Northing is known of the means of natural discharge from the Hickory aquifer in the subsurface. Water is also discharged artificially by wells. The heaviest concentration of wells is in southeastern McCulloch and northern Mason Counties.

### Water Levels

Although altitudes of water levels in wells completed in the Hickory aquifer do not vary greatly over short distances, the actual depths below land surface to water in individual wells often vary considerably due to differences of land-surface altitudes. In outcrop areas, water levels are within several feet of the surface. Away from the outcrop, depths to water generally increase with increasing distance downdip from the outcrop. This is mainly because in the downdip direction, water-level altitudes decrease, whereas land-surface altitudes generally increase. Depths to water from land surface generally range between 100 and 500 feet in the downdip portion of the aquifer. In some topographically low places, wells may flow naturally.

Water-level fluctuations in wells completed in the Hickory are the result of both natural and artificial causes. Natural water-level fluctuations result from changes in evapotranspiration and recharge. Water levels are lowest during summer months when evaporation and transpiration rates are highest and precipitation is usually low. Seasonal water-level fluctuations from these natural causes are usually small in the Hickory aquifer and rarely exceed 5 feet.

Water-level fluctuations due to pumping may become quite large, especially under artesian conditions. At the city of Brady, in McCulloch County, seasonal fluctuations of water levels in wells penetrating the Hickory aquifer are on the order of 50 feet. Although water levels at Brady have declined 90 feet since development from the Hickory aquifer began in 1930, the decline represents only development of the cone of depression and is not an overdraft of the aquifer (Mason, 1961, p. 32). In irrigated areas, pumping is seasonal and significant water-level declines generally do not occur. On the basis of available records there is little, if any, net decline in water levels from season to season as a result of irrigation development.

### Water-Bearing Characteristics

Values of coefficients of storage and transmissibility for the Hickory were obtained only in the northwestern part of the aquifer. A coefficient of storage of approximately 0.0001 was obtained at Brady, which is about 12 miles northwest of a Hickory outcrop. Coefficients of transmissibility obtained from wells in McCulloch and Mason Counties generally range from 18,000 to 40,000 gpd per foot. The lower values generally occurred at greater distances from the outcrop areas. These data were obtained from pumping tests of various time durations. Usually the wells were pumped for no longer than 4 hours. Several tests, including the one performed at Brady, were conducted over a 48-hour pumping period. Values of permeability were not calculated because of difficulty in determining the thickness of the water-bearing zones in the Hickory.

### Chemical Quality

Water in the Hickory aquifer is of a sodium bicarbonate type and, although sometimes objectionably hard, is generally suitable for most uses. The poorest quality of water recorded is in the vicinity of Eden, in Concho County, where the dissolved solids are approximately 1,000 to 1,500 ppm; but considering the distance from the outcrop and the depths at which the Hickory is encountered in the Eden area, the quality of the water is remarkably good. Analyses of water from representative wells in the Hickory aquifer are presented in Table 4, and sites from which water samples were collected are plotted on Plate 13.

Few contamination problems for the Hickory aquifer are anticipated except at great distances from the outcrop areas, where there may be a possibility of saline waters being drawn into a cone of depression caused by pumpage. Local contamination may result from salt-water leakage from overlying strata in uncased wells or from salt water entering a well through corroded casing and mixing with the fresh water from the Hickory aquifer. This has occurred at the city of Melvin, in McCulloch County, and may have also occurred at the city of Eden, in Concho County. Because this type of contamination seldom occurs, and because it can be remedied through proper application of well-completion and plugging methods, it is not considered a serious threat. Where Hickory water is obtained from great depths, high water temperatures may be objectionable, such that cooling facilities may be desirable.

## Utilization and Development

The Hickory aquifer is a source of water for irrigation, for small towns and communities, and for one industry, as well as for domestic and livestock-watering purposes.

Municipal pumpage from the Hickory aquifer is (in 1960) at Mason, in Mason County, Brady and Melvin, in McCulloch County, and Eden, in Concho County. Industrial pumpage supplies ground water for a sand-processing plant near Voca, in southeastern McCulloch County. Irrigation development from the Hickory aquifer is in several isolated areas in central and northern Mason County, southeastern McCulloch County, and southern San Saba County; the areas are readily identified on Plate 2 as dense patterns of major wells. The areas of irrigation pumpage are generally near or on the outcrops where favorable conditions of crop-supporting soil and shallow pumping lifts are encountered. Principal crops irrigated are oats, barley, cotton, peanuts, sweet potatoes, grain sorghum, and corn. Present rates of irrigation pumpage in the outcrop areas has scarcely had any effect on the aquifer (Mason, 1961, p. 32). Some irrigation wells have been installed for use only when crop yields are threatened by drought.

Significant development of the aquifer has occurred only since 1950. Pumpage probably reached its peak during the drought years, as many irrigation wells are currently not being used. Total pumpage from the Hickory aquifer in 1960 was about 10,000 acre-feet, of which 3,900 acre-feet was pumped for municipal use, 270 acre-feet for industrial use, and 6,000 acre-feet for irrigation. The estimate for 1960 irrigation pumpage is based principally on 1958 pumpage figures that are published in Bulletin 6018 (Texas Board of Water Engineers, 1960b). Pumpage from the Hickory aquifer for 1960 is presented, by major drainage subdivisions, in Table 5.

Pumping rates of wells in the Hickory aquifer are known to be as high as 1,500 gpm; however, the more common pumping rates of the major wells are on the order of 200 to 500 gpm. Specific capacities range from 2 to 18 gpm per foot of drawdown, but values of 7 to 9 gpm per foot of drawdown are most common. Specific capacities have been increased in several Hickory wells through the use of explosives applied to tightly-cemented sandstones in the wells.

Large-capacity Hickory wells are usually of the open-hole type where steel casing, from 6 to 16 inches in diameter, is set only through surface soils to the top of hard rock. Casing is also set through salt-water-bearing zones when they are encountered. Rarely, wells are cased to total depth, and the casing is perforated opposite the fresh-water strata.

Ground Water Available for Development

Because of complicated geologic and hydrologic conditions in the Hickory aquifer and because of lack of basic data, the quantity of water available for development from the aquifer can be only roughly estimated. The 1960 pumpage of only 10,000 acre-feet per year is small in comparison with the aquifer's large areal extent. Considering this pumpage-to-size relationship, it is presumed that the Hickory aquifer can furnish much more water to wells than has been developed. It seems reasonable that, with adequately-spaced wells, at least 50,000 acre-feet per year is available perennially for development from the Hickory aquifer; perhaps even larger quantities of water could be safety withdrawn.

## Other Aquifers

### Alluvium

Alluvial deposits consisting mostly of gravel occur along the Colorado River and its tributaries. These deposits, though often limited in area, are capable of supplying domestic and livestock wells and in some places are developed for public-supply and irrigation uses. The quality of water in the alluvium is suitable for most purposes.

Of particular interest to this study is the alluvium in association with the Concho River drainage system west of San Angelo. These deposits form terraces along the Concho River where they are believed to be as much as 250 feet thick in places. Although the saturated alluvial deposits in this area of Region II are treated separately in this report, they are hydrologically in connection with the Edwards-Trinity (Plateau) aquifer, as illustrated on Plate 4. Thus, it is merely a matter of choice that these deposits are mentioned here rather than as a part of the Edwards-Trinity (Plateau) aquifer of Region II.

In the Lipan Flats area of eastern Tom Green County, saturated alluvial gravels furnish ground water to most of the irrigation wells. Dissolved-solids content of water from these deposits generally ranges from 500 to 1,400 ppm, the predominant ions being calcium and bicarbonate, and in general the water is excessively hard. Although persistent water-table declines in these deposits will probably limit more widespread irrigation in this area, the supply should remain adequate for domestic and livestock wells.

In the central part of the Llano uplift, stream gravels derived from the granitic terrain are usually the only reliable source of ground water for domestic use.

### Permian Rocks

Several stratigraphic units of the Permian System are known to yield small to large amounts of usable water to wells in parts of Coke, Runnels, Coleman, Tom Green, and Concho Counties. Generally, Permian rocks are either too tight to yield water to wells or else they yield only small amounts of mineralized water. However, exceptions to the foregoing generalizations are found in the Standpipe Limestone Member of the Arroyo Formation and the Bullwagon Dolomite

Member of the Vale Formation, both of which belong to the Clear Fork Group and crop out in eastern Tom Green and western Runnels Counties. The Standpipe Limestone, a marly limestone approximately 15 feet thick, yields small amounts of usable water near outcrop areas. The Bullwagon Dolomite consists of 75 feet of massive dolomitic limestone interbedded with shale, and yields usable water in amounts up to as much as 1,000 gpm to a few wells west of its outcrop.

## Pennsylvanian Rocks

Although usable ground water is occasionally obtained from most of the Pennsylvanian rocks in Region II, the units which are most significant are in the Strawn and Bend Groups.

Sands of the Strawn Group yield small quantities of potable water to domestic and livestock wells in and near outcrop areas. These Strawn sands occur in southeastern Brown, southwestern Mills, northern San Saba, and northeastern McCulloch Counties.

Cavities and fractures in the Marble Falls Limestone of the Bend Group supply water to many wells in the Llano uplift area, but it is in San Saba County that this aquifer is most prolific. The cities of San Saba and Richland Springs, in San Saba County, obtain water from large springs in the Marble Falls Limestone, and an irrigation well yielding more than 2,000 gpm produces from a cavity in this limestone. The quality of water produced from the Marble Falls Limestone is usually suitable for most purposes in and near outcrop areas.

## Welge Sandstone Member of the Wilberns Formation

The Welge Sandstone Member of the Wilberns Formation, a medium- to coarse-grained sandstone averaging about 20 feet in thickness, yields small amounts of water where it crops out around and in the Llano uplift. It is a dependable source of water for domestic and livestock-watering purposes.

## Precambrian Rocks

In the central part of the Llano uplift where Precambrian rocks crop out at the surface, fractures developed in these rocks are often the only source of ground water for domestic supplies. Although water of good chemical quality is usually obtained, the amount available is small.

## Trinity Group (North-Central Texas)

As shown on Plate 2, rocks of the Trinity Group crop out along the northeastern basin boundary and have been separated from Trinity rocks of the Edwards Plateau by dissection of the Colorado River.

Sands at the base of the Trinity Group along the northeastern boundary are fine grained and seldom attain thicknesses greater than 30 feet. The sands furnish amall amounts of water to wells, usually less than 100 gpm. One well, however, is known to supply more than 200 gpm. Water from the Trinity Group sands in this area is of good quality and suitable for most purposes, although excessive hardness is sometimes objectionable. Sands of the Trinity Group furnish water to communities and small towns and to several irrigators, as well as to domestic and livestock wells.

Sands of the Trinity Group along the northeastern border of Region II extend eastward into the Brazos River basin, forming an areally extensive and important aquifer there.

## Region III

Unconsolidated sands underlying the Gulf Coastal Plain comprise the two secondary aquifers in Region III of the Colorado River basin; there are no primary aquifers in this region. The two secondary aquifers are: the Gulf Coast and the Carrizo-Wilcox. (See Figure 5, page 23.)

Other aquifers in Region III, those which supply small quantities of ground water locally for municipal, industrial, irrigation, domestic, or livestock-watering purposes, are: the Edwards Limestone (Balcones Fault Zone), the Trinity Group (North-Central Texas), Alluvium, the Queen City Formation, the Yegua Formation, and the Jackson Group.

Some of the data used in the following discussion of Region III are from a report on the ground-water resources of the Gulf Coast region of Texas prepared by personnel of the U.S. Geological Survey as part of the statewide reconnaissance program (Wood and others, 1963).

### Secondary Aquifers

#### Gulf Coast Aquifer

The Gulf Coast aquifer in Region III of the Colorado River basin consists of fresh-water-bearing (containing water having less than 3,000 ppm dissolved solids) sands of the Catahoula, Oakville, Lagarto, Goliad, Lissie, and Beaumont stratigraphic units (Table 1), and occurs over the entire southern half of the region, extending southeast from southeastern Fayette County to the mouth of the Colorado River at the Gulf Coast (Plate 15). The aquifer's northwestern boundary in Fayette County is based on thinning out of the saturated interval. The Gulf Coast aquifer extends out of the basin to the northeast, into the Brazos River and the Brazos-Colorado Coastal basins, and to the southwest, into the Guadalupe and the Lavaca River basins and the Colorado-Lavaca Coastal basin. To the southeast, the aquifer extends to the mouth of the Colorado River, where the depth to the base of fresh water (water having a dissolved-solids content of less than 3,000 ppm) is less than 600 feet.

##### Geologic Characteristics

The Gulf Coast aquifer in Region III is made up of six geologic formations, ranging in age from Miocene to Pleistocene. However, owing to the difficulty in differentiating these formations in the subsurface, they are commonly grouped into three units for discussion. The three groupings, from oldest to youngest in age, are: (1) the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay; (2) the Goliad Sand and Lissie Formation, and (3) the Beaumont Clay.

The Catahoula-Oakville-Lagarto unit crops out extensively in the southeastern part of Fayette County and in the northwestern part of Colorado County and dips toward the Gulf Coast at about 50 to 60 feet per mile. The Catahoula Sandstone, consisting of sand, conglomerate, and interbedded clay, silt, and tuff, is the basal formation of this unit. Excessive clay content limits the development potential of the Catahoula in the Colorado River basin. The Oakville Sandstone, which overlies the Catahoula, is a massive light-colored sand containing minor interbeds of clay. The Lagarto Clay is principally a massive clay with interbedded sand and sandy clay.

The Goliad-Lissie unit overlies the Catahoula-Oakville-Lagarto unit, and crops out in a relatively narrow band on either side of the Colorado River south and east of Columbus, in Colorado County. The outcrop of the Goliad-Lissie unit is small in area, and only the Lissie appears at the surface. These formations dip toward the Gulf at a rate ranging from 10 to 45 feet per mile. The basal formation of this unit, the Goliad Sand, is characteristically a coarse-grained sand interbedded with layers of gravel and clay. The Willis Sand, which occurs east of the basin, is not known to occur within the Colorado River basin. The Lissie Formation is composed of massive beds and lenses of fine- to coarse-grained sand which grade into and are interbedded with clay, sandy clay, and gravel.

The Beaumont Clay is principally a poorly bedded calcareous clay containing thin stringers and beds of silt and fine sand.

The sand units of the Gulf Coast aquifer which contain water with less than 3,000 ppm dissolved solids range in thickness from a featheredge inland to more than 1,000 feet in Wharton County. Water containing less than 3,000 ppm dissolved solids may be obtained from zones as deep as 2,600 feet. Approximate thickness of water-bearing sand containing less than 3,000 ppm dissolved soilds in the Gulf Coast aquifer is shown on Plate 14. From southeastern Colorado County toward the coast, the depth to the base of water containing less than 3,000 ppm dissolved solids becomes progressively shallower, and at the mouth of the Colorado River is less than 600 feet. Depth to base of water containing less than 3,000 ppm dissolved solids can be determined by comparing the contours of Plate 15 with the appropriate land-surface altitude.

### Occurrence and Movement of Ground Water

Both water-table and artesian conditions exist in the Gulf Coast aquifer. Where sands of the Gulf Coast aquifer are at the surface, water-table conditions generally occur. Artesian conditions are generally encountered downdip from outcrop areas of the sands, where water in the sands is confined beneath relatively impervious overlying materials. Most of the water in the Gulf Coast aquifer is under artesian conditions.

Where water-table conditions exist, ground water moves downdip and laterally from the area of recharge to points of discharge in topographically low areas, where the water is discharged at seeps. Where artesian conditions exist, movement of water is generally in the direction of the regional dip, from the outcrop area toward the Gulf Coast. Water levels in wells screened through deeper sands are higher than those in wells screened through shallower sands; and there is an upward vertical movement of water through confining beds, the rate of movement depending on vertical permeability, thickness of confining layers, and difference in hydraulic head.

### Recharge and Discharge

Conditions affecting recharge in the Gulf Coast aquifer are generally favorable, and it is likely that potentially available recharge is rejected in many of the sand outcrops.

Discharge from the aquifer is by both artificial and natural means. Artificial discharge occurs from wells which screen the aquifer, the greatest amount being produced by municipal, industrial, and irrigation wells of the region. An undetermined but significant amount of water is produced from domestic and livestock wells. Natural discharge occurs through seeps along drainage courses and through vertical interformational leakage.

### Water Levels

Water levels in the Gulf Coast aquifer are generally less than 100 feet below the land surface. Significant regional fluctuation of water levels is mostly seasonal, occurring in the irrigated areas of southern Colorado County and northwestern Wharton County.

### Water-Bearing Characteristics

Water-bearing characteristics of the Gulf Coast aquifer are highly variable because permeability and thickness of water-bearing sands vary greatly from place to place. Available data indicate that in sands containing less than 3,000 ppm dissolved soilds, coefficients of transmissibility range from less than 50,000 to more than 300,000 gpd per foot. The largest transmissibilities occur where the net sands of the aquifer are thickest.

Yields and specific capacities of wells vary greatly depending on permeability, thickness of the sand penetrated, and well construction. Specific capacities generally are less than 50 gpm per foot of drawdown, although wells in central Wharton County have specific capacities as high as 140 gpm per foot of drawdown. Individual well yields of 2,000 gpm are common. Few wells penetrate the entire thickness of the aquifer. In general, the Goliad-Lissie unit is the most prolific portion of the Gulf Coast aquifer.

### Chemical Quality

Ground water of good to excellent quality may be obtained from the Gulf Coast aquifer in Region III. Seclected chemical analyses of water from the aquifer, approximate locations of wells sampled, and producing intervals are presented in Table 6. These analyses are believed to be representative of the quality of water in the Gulf Coast aquifer in the Colorado River basin for the designated locations and producing intervals.

Although water suitable for most purposes may be found in the Gulf Coast aquifer throughout the basin, treatment is usually necessary where chemical quality is a critical factor, for municipal and industrial uses. Generally, waters lowest in total hardness are found in zones deeper than 500 feet, but these waters have larger concentrations of bicarbonate than waters from shallower zones. The water is apparently suitable for present (1960) irrigaton

Table 6.--Representative chemical analyses of water from secondary aquifers, Region III, Colorado River basin

(Analyses expressed in parts per million except specific conductance and pH.)

| Well or analysis no. | Location of well | Screened interval (feet) | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium and potassium (Na + K) | | Bicarbonate ($HCO_3$) a/ | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids b/ | Total hardness as $CaCO_3$ | Specific conductance (micromhos at 25°C.) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gulf Coast Aquifer** | | | | | | | | | | | | | | | | | |
| 66-03-8 | Fayetteville | c/768-902 | 60 | 0.02 | 5.6 | 0.5 | 240 | | 534 | 31 | 48 | 0.2 | 0 | 648 | 16 | -- | -- |
| 18-5 | Weimer | ? -605 | 18 | .14 | 30 | 8.7 | 167 | 6.6 | 347 | 7.6 | 133 | .5 | .5 | 558 | 111 | -- | 8.4 |
| d/ 5 | Columbus | 40- 48 | 13 | e/ .02 | 115 | 10 | 13 | 4.8 | 352 | 18 | 19 | .2 | 34 | 407 | 328 | 668 | 8.4 |
| d/ 6 | Eagle Lake | c/360-525 | 29 | .01 | 44 | 3.2 | 16 | 1.4 | 144 | 4.2 | 28 | .2 | .5 | 198 | 123 | 326 | 7.6 |
| d/ 7 | 7 mi. W Eagle Lake, Colorado Co. | c/100-601 | 28 | -- | 37 | 5.3 | 85 | -- | 255 | 8.9 | 52 | -- | .5 | 342 | 114 | 563 | 8.0 |
| d/ 8 | 22 mi. SW Eagle Lake, Colorado Co. | 703-804 | 26 | -- | 66 | 5.9 | 28 | 1.8 | 238 | 6.8 | 44 | -- | .0 | 300 | 189 | 495 | 7.6 |
| d/ 22 | 11 mi. W Wharton, Wharton Co. | c/ 77-186 | 24 | -- | 60 | 6.7 | 23 | 1.7 | 220 | 6.0 | 28 | .2 | 3.2 | 264 | 177 | 440 | 7.5 |
| d/ 23 | Wharton, Wharton Co. | c/212-393 | -- | e/ .15 | 67 | 14 | 32 | | 256 | 16 | 47 | -- | .8 | 303 | 225 | -- | -- |
| d/ 36 | 14 mi. S Bay City, Matagorda Co. | 150-720 | 21 | -- | 37 | 8.8 | 143 | -- | 366 | 11 | 90 | -- | .2 | 498 | 128 | 849 | 8.0 |
| d/ 38 | 19 mi. SW Bay City, Matagorda Co. | c/ 85-466 | 28 | -- | 62 | 30 | 143 | 1.9 | 422 | 46 | 140 | .6 | .0 | 671 | 278 | 1,160 | 7.0 |
| **Carrizo-Wilcox Aquifer** | | | | | | | | | | | | | | | | | |
| 58-46-5 | Elgin, Bastrop Co. | 120 | 29 | 0.01 | 26 | 7.6 | 41 | 6.2 | 41 | 28 | 91 | 0.3 | 1.8 | 272 | 96 | 442 | 6.5 |
| 47-7 | McDade, Bastrop Co. | -- | 32 | .05 | 82 | 19 | 49 | 4.5 | 223 | 134 | 51 | .7 | .2 | 502 | 282 | 762 | 7.3 |
| 54-5 | 5 mi. N Bastrop, Bastrop Co. | 559 | 40 | .58 | 102 | 14 | 57 | | 228 | 148 | 67 | .2 | .0 | 546 | 312 | 791 | 7.7 |
| 61-3 | 5 mi. W Bastrop, Bastrop Co. | 59 | 46 | .46 | 148 | 22 | 65 | | 262 | 80 | 214 | .0 | .5 | 705 | 460 | 1,230 | 6.9 |
| 63-7 | 8 mi. SE Bastrop, Bastrop Co. | 391 | 14 | -- | 2.0 | .0 | 106 | .9 | 255 | 10 | 15 | -- | .0 | 273 | 5 | 456 | 7.8 |
| 67-05-2 | 13 mi. SE Bastrop, Bastrop Co. | 600 | 24 | -- | 18 | 16 | 334 | | 521 | 184 | 166 | -- | 0 | 1,010 | 111 | 1,660 | 8.0 |
| 06-2 | 2 mi. S Bastrop, Bastrop Co. | 125 | 74 | 7.6 | 5.3 | 3.4 | 39 | | 4 | 32 | 53 | -- | .0 | 227 | 27 | 259 | 5.2 |

a/ Includes equivalent of any carbonate ($CO_3$) present.
b/ Some analyses include the sum of the total constituents; others, about half the bicarbonates.
c/ Not screened throughout interval.
d/ Analysis from Wood, Gabrysch, and Marvin (1963).
e/ Iron in solution at time of analysis.

uses. Hardness and iron content for some public-supply systems is undesirable, and treatment is commonly used to reduce concentration of these adverse constituents. Otherwise, chemical quality is within the limits prescribed by U.S. Public Health Service standards. The dissolved-solids content of waters produced from the Gulf Coast aquifer ranges from about 200 to about 700 ppm.

Quality of water in some parts of Region III, especially near the coastal area, may be threatened by salt-water encroachment, and heavy pumping may cause saline water to move up the formational dip or vertically through confining layers to points of discharge.

### Utilization and Development

On the basis of 1959 pumpage figures, it is estimated that about 18,000 acre-feet of ground water is being produced yearly for municipal, industrial, and irrigation purposes from the Gulf Coast aquifer in Region III. Most of the production, about 17,000 acre-feet per year, is for irrigation. Public supply and industrial pumpage total about 820 and 300 acre-feet per year, respectively.

The greatest development of ground water in Region III is in the northwestern part of Wharton County and in the southern part of Colorado County where rice is irrigated extensively. Ground water is the source for all public supplies in the region. Plate 3 shows the location and distribution of municipal, industrial, and irrigation wells in Region III. It is estimated that the municipal, industrial, and irrigation pumpage figures listed above represent about 90 percent of the total production of the Gulf Coast aquifers; domestic and livestock wells account for the remaining pumpage. A summary of municipal, industrial, and irrigation pumpage from the Gulf Coast aquifer in Region III, by major drainage subdivisions, is presented in Table 7.

At the 1960 stage of development, significant regional problems resulting from ground-water withdrawals were not apparent. In the Gulf Coast aquifer, as in all coastal aquifers, salt-water encroachment from extensive pumping is a potential threat. Although land subsidence has not been observed in Region III, it may occur should water levels be lowered such that a large amount of fine material in the subsurface is dewatered. Further investigation will be necessary to adequately realize the difficulties that may be encountered with increasing development.

### Ground Water Available for Development

Available pumpage figures for the Gulf Coast aquifer in Region III show that in 1959 about 18,000 acre-feet was produced for municipal, industrial, and irrigation purposes. Future increases in development in areas downdip from outcrops of water-bearing sands will cause increases in hydraulic gradients. It is estimated that under maximum gradients about 33,000 acre-feet of water per year would move through the aquifer, and thus be available on a perennial basis. About 3 of the 40 inches of annual rainfall would be needed as recharge to support maximum conditions of development. It is believed that aquifer outcrop conditions are such that even at maximum development, recharge would be greater than the amount needed for withdrawals. Therefore, it should be possible not only to sustain maximum development but also to develop additional water supplies in the outcrop area. Additional water would be produced

Table 7.--1960 Ground-water pumpage from aquifers in Region III, Colorado River basin

(Pumpage, some of which is estimated, is in acre-feet, and should be considered accurate to no more than two significant figures. Irrigation pumpage partly for 1958 (Texas Board of Water Engineers, 1960b).)

| Use | 1960 Pumpage, by major drainage subdivision | | | | | | Total 1960 pumpage |
|---|---|---|---|---|---|---|---|
| | 60 | 61 | 63 | 64 | 65 | 66 | |
| **Gulf Coast Aquifer*** | | | | | | | |
| Municipal | -- | -- | -- | 350 | 473 | -- | 823 |
| Industrial | -- | -- | -- | -- | 56 | 246 | 302 |
| Irrigation | -- | -- | -- | 105 | 3,500 | 13,100 | 16,705 |
| Subtotal | -- | -- | -- | 455 | 4,029 | 13,346 | 17,830 |
| **Carrizo-Wilcox Aquifer** | | | | | | | |
| Municipal | -- | 396 | 277 | -- | -- | -- | 673 |
| Industrial | -- | -- | -- | -- | -- | -- | -- |
| Irrigation | -- | 20 | -- | -- | -- | -- | 20 |
| Subtotal | -- | 416 | 277 | -- | -- | -- | 693 |
| **Other Aquifers†** | | | | | | | |
| Municipal | 109 | 262 | 241 | 574 | -- | -- | 1,186 |
| Industrial | -- | -- | -- | -- | -- | -- | -- |
| Irrigation | 330 | 30 | -- | 70 | -- | -- | 430 |
| Subtotal | 439 | 292 | 241 | 644 | -- | -- | 1,616 |
| **Summary of Pumpage in Region III** | | | | | | | |
| Municipal | 109 | 658 | 518 | 924 | 473 | -- | 2,682 |
| Industrial | -- | -- | -- | -- | 56 | 246 | 302 |
| Irrigation | 330 | 50 | -- | 175 | 3,500 | 13,100 | 17,155 |
| Total | 439 | 708 | 518 | 1,099 | 4,029 | 13,346 | 20,139 |

* Pumpage mostly for 1959 from Wood, Gabrysch, and Marvin (1963).

† Trinity Group (North-Central Texas), Edwards Limestone (Balcones fault zone), Queen City Formation, Yegua Formation, Jackson Group, and alluvium.

from storage during development from present to maximum conditions, but this additional water would not be available on a perennial basis.

For discussions on the methods used in determining the quantity of water available from the Gulf Coast aquifer, the reader is referred to Wood and others (1963).

## Carrizo-Wilcox Aquifer

Although the Carrizo-Wilcox aquifer is of primary importance over most of the Texas Gulf Coastal Plain, it is classified as secondary in the Colorado River basin because of the limited areal extent imposed on it by the boundaries of the basin. To date, development of the Carrizo-Wilcox in the Colorado River basin has been small.

### Geologic Characteristics

The Carrizo-Wilcox aquifer crops out in a broad band through a large part of Bastrop County. Beds dip approximately 100 to 150 feet per mile toward the coast, as shown on Plate 16. Thickness of the part of Carrizo-Wilcox which contains water having less than 3,000 ppm dissolved solids ranges from near zero at the edge of the outcrop to more than 2,500 feet in the southeastern part of Bastrop County. The portion of the aquifer containing water with less than 3,000 ppm dissolved solids extends down the river basin to about LaGrange, in Fayette County. Variations in thickness of the Carrizo-Wilcox aquifer are shown on Plate 17. The Carrizo-Wilcox is typically composed of lenses of sand and clay with beds of lignite that occur mostly in the lower part of the Wilcox. At and near the surface, the sands of the Carrizo-Wilcox are generally cemented with iron. The Wilcox Group is geologically subdivided into three formations which are from top to bottom the Sabinetown, Rockdale, and Seguin. The Rockdale is the most prolific water-bearing unit in the Wilcox. The Carrizo Formation of the Claiborne Group overlies the Wilcox Group and is composed almost entirely of unconsolidated sand. Sands generally comprise more than 50 percent of the Carrizo-Wilcox unit.

### Occurrence and Movement of Ground Water

Both water-table and artesian conditions exist in the Carrizo-Wilcox aquifer. Where sands of the Carrizo-Wilcox crop out, water-table conditions occur. Artesian conditions are generally encountered downdip from outcrop areas of sands, where water in the sands is confined beneath relatively impervious overlying materials.

Where water-table conditions exist, ground water moves downdip and laterally from the area of recharge to points of discharge in topographically low areas, where the water is discharged at seeps. Where artesian conditions exist, movement of water is generally in the direction of the regional dip, toward the Gulf Coast. Because individual sands in the Carrizo-Wilcox crop out and are recharged at different elevations, waters in individual sands are under different hydraulic head, and there is some interformational movement of water. The rate of this movement depends on vertical permeability, thickness of confining layers, and difference in hydraulic head.

### Recharge and Discharge

Fresh water in the Carrizo-Wilcox aquifer is believed to be derived almost entirely from precipitation which falls on the outcrop. The aquifer does not appear to receive water from other geologic formations because it is underlain by very tight clay of the Midway Group and overlain by tight sand and clay of the Reklaw Formation. However, the rate of recharge to the aquifer is perhaps large, since the outcrop is covered with deep sandy soils and rainfall on the outcrop is plentiful. Much of the potential recharge is rejected.

Water is discharged from the aquifer by both artificial and natural means. Artificial discharge is by wells which screen the aquifer; a large amount of water is produced by municipal and irrigation wells in the region, and an undetermined but significant amount of water is produced by domestic and livestock wells. Natural discharge is in the form of subsurface interformational leakage and by springs and seeps along principal surface drainage courses.

### Water Levels

Depth of water in wells in the Carrizo-Wilcox aquifer depends mostly upon the topography at the well site. Along topographic highs depth to water is often more than 200 feet, and in low areas, such as along the flood plains of the Colorado River, flowing wells are present. Because individual sands in the Carrizo-Wilcox aquifer are under different hydraulic head, depth to water depends also upon the section of sand screened by the well. Available data on water levels in wells in the Carrizo-Wilcox aquifer show that very little net change in water levels has occurred in the past two decades.

### Water-Bearing Characteristics

Water-bearing characteristics of the Carrizo-Wilcox aquifer are believed to be highly variable because permeability and thickness of water-bearing sands vary greatly from place to place. The only available data on the water-bearing characteristics of the Carrizo-Wilcox aquifer in Region III of the Colorado River basin is from pumping tests performed at Camp Swift near the city of Bastrop (Guyton, 1942). Tests at Camp Swift were performed on several wells screened through about 200 feet of sand in the middle part of the Wilcox Group. The pumping tests, which ranged in duration from several hours to several days, employed both drawdown and recovery methods. Coefficients of transmissibility generally ranged from 25,000 to 80,000 gpd per foot; storage coefficients ranged from 0.0003 to 0.0012. Larger coefficients of transmissibility and storage are expected in areas having greater sand thickness.

Data from the Camp Swift pumping tests were used to construct a distance-drawdown graph (Figure 11), which shows the expected drawdown at various distances from a well pumping 1,000 gpm from a 200-foot thick section of sand in the Carrizo-Wilcox aquifer. Although the information presented on the graph is of a theoretical nature, the graph should nevertheless be useful for estimating effects on the aquifer caused by pumping. Because drawdown is proportional to rate of pumping, drawdowns resulting from pumping of a well at a rate other than 1,000 gpm are easily computed from the information shown on the graph.

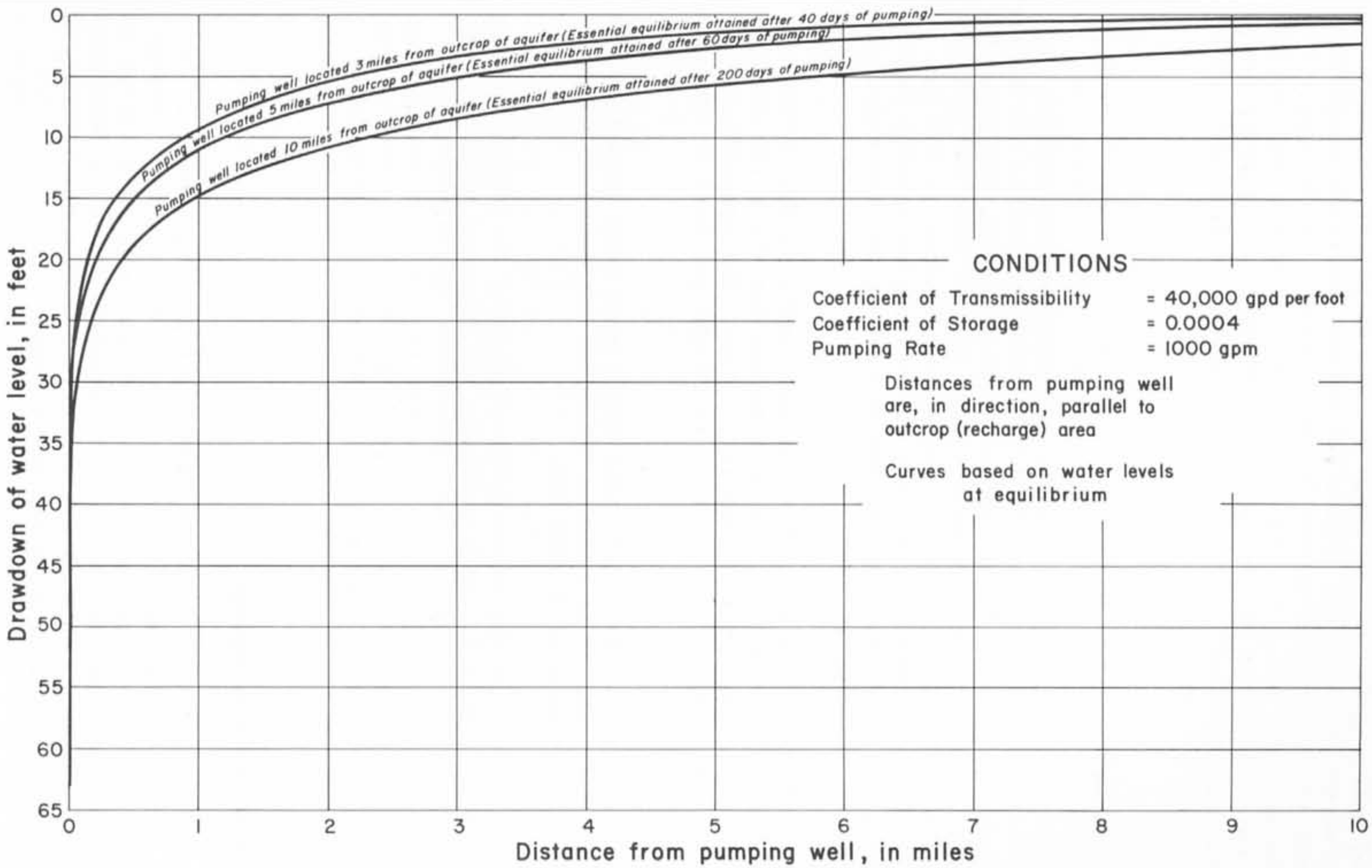



Figure 11

Distance-Drawdown Curves for Wells Pumping From Carrizo-Wilcox Aquifer at Various Distances From Outcrop Area, Region III, Colorado River Basin

Texas Water Development Board in cooperation with the U. S. Geological Survey

## Chemical Quality

Quality of water in the Carrizo-Wilcox aquifer varies considerably, as shown by analyses of waters presented in Table 6. The locations corresponding to the analyses are shown on Plate 16. Dissolved solids generally range from 200 to 1,000 ppm, and total hardness generally ranges from 5 to 460 ppm. Values of pH vary between 5.2 and 8.0. Generally, total hardness and concentration of iron in Carrizo-Wilcox waters decrease with increasing depth in the producing zone. The only treatment which may be necessary or desirable would be for reduction of iron concentration or hardness.

## Utilization and Development

The few major wells producing water from the Carrizo-Wilcox aquifer in Region III are completed with large diameter surface casing that is set to the top of the water-producing zones. Producing zones are screened, and generally underreamed and gravel packed. Although well yields greater than 600 gpm are known, the average yield of wells in the Carrizo-Wilcox aquifer is 200 gpm. Failures of wells in the Carrizo-Wilcox aquifer in this region usually result from corrosion or plugging, and based on records of five wells, the expected life of a well is on the order of 10 years.

Specific-capacity figures are available for many wells in the Carrizo-Wilcox aquifer in Region III. However, the only values for which the pumping duration was reported were those in the Camp Swift area. The specific capacities obtained from these ranged from about 10 to 20 gpm per foot of drawdown after 1 1/2 hours of pumping.

All but two of the eight wells in the Camp Swift area were unused in 1960, but during their period of greater production the wells furnished an adequate supply of water for an army camp of 50,000 men.

In 1960, major pumpage from the Carrizo-Wilcox aquifer in Region III was mostly for public supply. Table 7, which presents the reported major pumpage by major drainage subdivisions in Region III, shows that approximately 690 acre-feet was pumped from the Carrizo-Wilcox aquifer in 1960. Of this amount, about 20 acre-feet was for irrigation and 670 acre-feet was for public supply. An undetermined amount of water is also pumped for domestic and livestock-watering purposes.

## Ground Water Available for Development

On the basis of data obtained from the Camp Swift pumping tests, it is estimated that the Carrizo-Wilcox aquifer is capable of sustaining increased pumpage and that if as much as 10 percent of the average annual precipitation on the outcrop could be recharged to the aquifer, about 60,000 acre-feet per year of water would be available on a perennial basis. During development, additional water would be available from aquifer storage.

## Other Aquifers

### Edwards Limestone (Balcones Fault Zone)

The Edwards Limestone and possibly other limestone units in the Balcones fault zone of Region III furnish water to a few wells and to one large spring. The availability of water from the Edwards Limestone (Balcones Fault Zone) aquifer is not estimated because information is not available on which to base a sound, reasonable estimate. Dissolved-solids content of the water ranges from a few hundred to more than 5,000 ppm. Yields of wells also vary considerably. Barton Springs at the city of Austin, in Travis County, sustains an average flow of approximately 40 cubic feet per second. Several miles southeast of the fault zone, water in the Edwards Limestone is of such poor quality that it is not usable for most purposes.

### Trinity Group (North-Central Texas)

Sands of the Trinity Group (North-Central Texas), which occur over a large area in the Brazos River basin, extend into Region III of the Colorado River basin and yield potable water to wells in Travis County. The sands generally do not yield large quantities of water to wells; however, they are an important source of water for small communities near the city of Austin. The city of Manor, which is several miles east of Austin, obtains water containing about 1,800 ppm dissolved solids from a depth of approximately 3,000 feet below land surface. The wells at Manor yield approximately 100 gpm, and when first drilled they were reported to have had a static water level greater than 80 feet above land surface. Northwest of Austin, sands of the Trinity Group (North-Central Texas), where present, supply potable water to small-yield wells.

### Alluvium

Alluvial deposits, consisting of sand and lenses of gravel associated with the development of the Colorado River and its tributaries, are capable of furnishing large supplies of water to wells in areas of greatest saturated thickness. The only public-supply system in Region III which obtains water from the alluvium is that of the city of Bastrop. The alluvium is recharged directly by infiltration from the river. The chemical quality of water in the alluvium is good, being similar to that in the Colorado River.

### Queen City Formation

The Queen City Formation crops out in a narrow band across the Colorado River basin between Bastrop and Smithville (Plate 3). The aggregate thickness of sands within the Queen City is as much as 200 feet along the eastern margin of the basin where the Queen City is best suited for development. The Queen City adequately supplies the cities of Smithville, in Bastrop County, and Giddings, in Lee County.

## Yegua Formation

The Yegua Formation crops out across the basin principally in northwest Fayette County (Plate 3). The Yegua consists of sand and clay and furnishes water to a few irrigation wells in Region III. Southwest of the basin area, in southwest Fayette County, the city of Flatonia has developed an adequate public-supply system from sands of the Yegua. Several irrigation wells in the Flatonia vicinity also produce water from the Yegua.

## Jackson Group

Sands of the Jackson Group, which crops out across a large area of central Fayette County north of La Grange (Plate 3), yield small to moderate supplies of water in Region III. Because the Jackson consists mostly of fine-grained materials associated with volcanic activity, most of its strata are not capable of furnishing adequate water for large-yield wells. However, lenticular sands in the upper Jackson furnish water for the city of La Grange as well as for irrigation purposes. The quality of water from the Jackson sands is suitable for most purposes in and near the outcrop.

## Summary of Ground-Water Pumpage and Availability

Approximately 820,000 acre-feet of ground water was pumped in 1960 from the aquifers of the Colorado River basin for municipal, industrial, and irrigation purposes. About 90 percent of this pumpage, or approximately 750,000 acre-feet, was in Region I of the basin. About 95 percent of the water pumped in Region I was used for irrigation. Only about 50,000 acre-feet of ground water was pumped annually from aquifers in Region II, where the water was used primarily for irrigation. Most of the approximately 20,000 acre-feet of ground water pumped in Region III was also used for irrigation. A summary of pumpage from the aquifers of the Colorado River basin for 1960 is presented in Table 8.

Because of variable recharge conditions in the Colorado River basin, the amounts of ground water available for development must be considered under different conditions, as follows:

(1) Where recharge to the aquifer is significant, water is available for major development on a perennial basis.

(2) Where recharge to the aquifer is not significant in relation to the amount of water being pumped, only a portion of the water stored in the aquifer is considered available for development, and the aquifer is subject to depletion. Recharge is inadequate to sustain major development only in Region I and in the extreme northwestern part of Region II.

Where significant recharge occurs, on the order of 300,000 to 400,000 acre-feet of ground water is estimated to be available annually from the primary and secondary aquifers of the Colorado River basin; practically all of this water is available for additional future development. Where recharge is not significant, on the order of 30,000,000 to 50,000,000 acre-feet of ground water is estimated to be available from storage in the primary and secondary aquifers of the basin; it should be emphasized that this quantity of water is

Table 8.--1960 Ground-water pumpage from aquifers in the Colorado River basin

(Pumpage, some of which is estimated, is in acre-feet, and should be considered accurate to no more than two significant figures. Aquifers: (P), primary aquifer; (S), secondary aquifer.)

| Aquifer | 1960 Pumpage, by use | | | Total 1960 pumpage |
|---|---|---|---|---|
| | Municipal | Industrial | Irrigation | |
| **Region I** | | | | |
| Ogallala (P) | 19,476 | 7,024 | 660,957 | 687,457 |
| Edwards-Trinity (Plateau) (P) | 2,702 | 5,821 | 120 | 8,643 |
| Edwards-Trinity (High Plains) (S) | 134 | 191 | 2,247 | 2,572 |
| Santa Rosa (S) | 229 | 7,141 | 37,306 | 44,676 |
| Others1/ | 14 | 154 | 1,824 | 1,992 |
| Subtotal | 22,555 | 20,331 | 702,454 | 745,340 |
| **Region II** | | | | |
| Edwards-Trinity (Plateau) (P) | 1,194 | 2,674 | 22,867 | 26,735 |
| Santa Rosa (S) | -- | -- | 269 | 269 |
| Ellenburger-San Saba (S) | 803 | -- | 486 | 1,289 |
| Hickory (S) | 3,933 | 274 | 5,956 | 10,163 |
| Others2/ | 2,764 | -- | 8,450 | 11,214 |
| Subtotal | 8,694 | 2,948 | 38,028 | 49,670 |
| **Region III** | | | | |
| Gulf Coast (S) | 823 | 302 | 16,705 | 17,830 |
| Carrizo-Wilcox (S) | 673 | -- | 20 | 693 |
| Others3/ | 1,186 | -- | 430 | 1,616 |
| Subtotal | 2,682 | 302 | 17,155 | 20,139 |
| **Total, All Regions** | | | | |
| Total | 33,931 | 23,581 | 757,637 | 815,149 |

1/ Chinle Formation, Cretaceous rocks (outliers), and alluvium.

2/ Precambrian rocks, Welge Sandstone Member of the Wilberns Formation, Pennsylvanian rocks, Permian rocks, Trinity Group (North-Central Texas), and alluvium.

3/ Trinity Group (North-Central Texas), Edwards Limestone (Balcones fault zone), Queen City Formation, Yegua Formation, Jackson Group, and alluvium.

estimated to be available on the basis of dewatering the aquifers and is available only once. These estimates are based on pumpage under idealized conditions.

The primary and secondary aquifers in Region I are the Ogallala, the Edwards-Trinity (Plateau), the Edwards-Trinity (High Plains), and the Santa Rosa. In these aquifers an estimated 20,000,000 to 30,000,000 acre-feet off water is available for development from ground-water storage. In addition to the ground-water available from storage, at least 30,000 to 40,000 acre-feet per year is available perennially from the Santa Rosa aquifer.

Primary and secondary aquifers in Region II are the Edwards-Trinity (Plateau), the Ellenburger-San Saba, and the Hickory. An estimated 200,000 to 300,000 acre-feet of ground water per year is available perennially from these aquifers. In addition, at least an estimated 10,000,000 to 20,000,000 acre-feet of water is available from storage in the Edwards-Trinity (Plateau) aquifer in the northwestern part of Region II where recharge is inadequate for sustained major development.

There are no primary aquifers in Region III; the Gulf Coast and the Carrizo-Wilcox are the two secondary aquifers in the region. From these two secondary aquifers an estimated 90,000 acre-feet of ground water per year is available on a perennial basis. Additional quantities of water can be developed in the outcrop areas of these aquifers where more water is available as recharge than can be transmitted to the areas of pumpage by the aquifers. Also, in attaining maximum development, large quantities of water will be withdrawn from storage. However, this water from storage is available only once and should not be considered as water available for development on a sustained basis.

## RECOMMENDATIONS FOR FUTURE STUDIES

For detailed water planning or for the planning of individual water supplies, more detailed information than is contained in this report is needed. Detailed ground-water investigations, as outlined in a report to the Fifty-Sixth Legislature (Texas Board of Water Engineers, 1958), should be made on the eight primary and secondary aquifers of the Colorado River basin to better define the water-bearing characteristics of each aquifer and to refine the ground-water-availability estimates presented in this report. These aquifer-oriented studies should not be restricted to an aquifer's occurrence within the Colorado River basin, but rather, they should include the entire areal extent of each aquifer (transcending basin boundaries where necessary) so as to permit a determination of what effects the geology and pumping outside the basin will have on ground-water availability within the basin. In addition to studies of the primary and secondary aquifers of the basin, investigations are needed to define the occurrence, quality, and availability of water in the Chinle Formation and in the Trinity Group (North-Central Texas), because these stratigraphic units occur in areas in which no other ground water is available.

Ground-water studies should be made in the vicinity of towns needing additional water, to estimate the quantity of ground water available for development. These studies should be made as the need arises for either a new water supply or for the expansion of an existing supply.

Continuing studies are needed to collect, compile, and periodically analyze records of pumpage, water levels, and chemical quality of water. Additional work is needed in the collection of water-use data to improve the quality of data received, and the program should be expanded to include irrigation pumpage. Additional water-level observation wells are needed in all of the primary and secondary aquifers of the Colorado River basin. These wells should be spaced throughout the aquifers, and additional observation wells should be located in the areas of pumpage. Data from the continuing water-use and water-level programs will provide a means for determining the effects of present and future pumpage. A continuing observation program of the chemical quality of water in the primary and secondary aquifers should be established to determine changes in the chemical quality that may affect the quantity of fresh ground water available for development. Wells should be sampled periodically throughout the extent of the aquifers, and special attention should be given to areas of heavy withdrawals and in the vicinity of oil-field activities.

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