TEXAS WATER DEVELOPMENT BOARD

REPORT 195

GROUND-WATER RESOURCES OF PART OF CENTRAL TEXAS WITH EMPHASIS ON THE ANTLERS AND TRAVIS PEAK FORMATIONS

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By

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DEDICATION

This report is dedicated to the memory of Robert D. Perkins, one of its authors. Bob, his wife, and two daughters were victims of a plane crash near Temple, Texas on November 17, 1972. Another employee of the Texas Water Development Board, Joe Henry, was also lost in this unfortunate accident.

Bob, a native of Stephenville in Erath County, was born December 8, 1940. He attended Tarleton State College, and in 1966 received a Bachelor of Science Degree in Geology from Texas Tech University. While at Texas Tech, he was President of the Geology Club in 1962-63 and a member of the Sigma Gamma Epsilon honorary geology fraternity.

Bob joined the staff of the Water Development Board in February 1966 and worked in the Waco field office until December 1971 when he transferred to El Paso as head of the regional field office of that city.

The Board and its staff pay tribute here to Bob Perkins' fine work and express our deep feeling over the very tragic loss of this highly skilled professional.

GROUND-WATER RESOURCES OF PART OF CENTRAL TEXAS WITH EMPHASIS ON THE ANTLERS AND TRAVIS PEAK FORMATIONS

ABSTRACT

The area covered by this report includes all or parts of Bell, Bosque, Brown, Burnet, Callahan, Comanche, Coryell, Eastland, Ellis, Erath, Falls, Hamilton, Hill, Hood, Johnson, Lampasas, Limestone, McLennan, Milam, Mills, Navarro, Somervell, Travis, and Williamson Counties in the central part of Texas. It has a population of about 846,000 (1970) and an area of 13,888 square miles. The economy of this region is supported principally by light industry, governmental agencies, and agriculture. The cities of Waco and Temple are important manufacturing centers. Irrigation from ground-water sources is practiced in Comanche, Eastland, Erath, and adjacent counties. The production of oil and gas also contributes to the economy in the northwest and eastern areas. Ground water, used extensively for peanut irrigation, public supply, and industry, is essential to the present and future welfare of the region.

The geologic units of the study region generally consist of a southeast-dipping sequence of Cretaceous rocks which uncomformably overlies a complex of Paleozoic and older rocks. The principal aquifers are of Cretaceous age and consist of sand and limestone units. The Antlers and Travis Peak Formations, which are hydrologically connected in Brown, Comanche, and Eastland Counties, are the most important aquifers. These formations extend on the surface or in the subsurface through essentially the entire study region. The Travis Peak Formation contains the Hensell and Hosston Members which are the two most important water-bearing units. Other important water-bearing units are the Glen Rose Formation, Paluxy Formation, Edwards and associated limestones, and the Woodbine Group.

Fresh ground water containing less than 1,000 milligrams per liter (mg/l) dissolved solids is available from the Cretaceous aquifers throughout most of the study region. The Travis Peak Formation generally yields water of good chemical quality with an approximate dissolved solids range of 300 to 3,000 mg/l within the region. In general, the water becomes more saline with depth. Ground water suitable for irrigation is produced from the Antlers and Travis Peak Formations in Comanche, Eastland, Erath, and adjacent counties. Most of the water from the Travis Peak Formation, with proper treatment, will meet industrial requirements. Water from the Travis Peak Formation is generally suitable for public supplies throughout most of the region.

Approximately 48,600 acre-feet of ground water in the study region was pumped from the principal Cretaceous aquifers in 1967. Of this amount, about 42,500 acre-feet was from the Antlers and Travis Peak Formations with additional withdrawals of 3,290 acre-feet from the Edwards and associated limestones, 1,200 acre-feet from the Glen Rose Formation, 1,060 acre-feet from the Paluxy Formation, and 580 acre-feet from the Woodbine Group. In 1967, the Antlers and Travis Peak Formations yielded about 16,800 acre-feet of water for public supply, about 16,100 acre-feet for irrigation, about 5,900 acre-feet for rural domestic use and livestock, and about 3,700 acre-feet for industrial use.

Water levels of the principal Cretaceous aquifers in the study region are generally declining. The amount of decline ranges from a few feet to 450 feet in 1967 in the Waco area where the supply is from the Travis Peak Formation. The amount of fresh water being withdrawn from the Hensell and Hosston aquifers in parts of Bell, Coryell, Hill, and McLennan Counties exceeds the estimates of recharge, and the ground-water supply is being depleted by removal of water from storage. Digital computer aquifer simulation studies of the Travis Peak Formation to the year 2020 indicate that tremendous water-level declines should occur downdip in the existing areas of heavy pumpage as a result of projected pumpage. Small water-level declines have been noted in the Paluxy Formation and the Woodbine Group, while only seasonal water-level fluctuations have been observed in the Glen Rose Formation and the Edwards and associated limestones.

Large quantities of ground water of good quality are available for development in the study region. Approximately 87,000 acre-feet of ground water could be pumped annually until the year 2020 from the Antlers and Travis Peak Formations under optimum conditions. Based on estimated recharge in the outcrop and a digital computer simulation of pumpage and water-level declines, this would not lower water levels to a depth greater than 400 to 500 feet below the surface of the ground or below the top of the water-bearing sands until the year 2020. An estimated 1,836 acre-feet of water is available from the Woodbine Group and approximately 930 acre-feet is available from the Paluxy Formation. These amounts can be pumped annually without lowering the static water levels below the top of the aquifer or below 400 feet below land surface. More detailed information is needed to determine the quantity of water available from the Glen Rose Formation and the Edwards and associated limestones.

Continuing programs are needed to collect basic data such as fluctuations of water levels, chemical analyses of water samples, and inventory of pumpage. In addition, pumping tests and recharge studies are needed in the outcrop areas. Data from these continuing programs, pumping tests, and recharge studies can be used to provide a basis for any needed adjustments to the digital computer model of the Hensell and Hosston aquifers.

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INTRODUCTION

Purpose and Scope

Field investigations were conducted during the period from September 1964 to September 1969 to determine the ground-water resources of part of the central Texas region, with emphasis on the Antlers and Travis Peak Formations. The Travis Peak Formation contains the Hensell and Hosston Members, which are the two most important water-bearing units of this region. The study region is shown on Figure 1.

The primary purpose of this investigation was to determine the occurrence, availability, dependability, quality, and quantity of ground water used for public supply, industry, and irrigation, from the Antlers and Travis Peak Formations, and to establish a relationship between pumpage and water-level decline. The secondary purpose was to determine the occurrence, availability, dependability, quality, and quantity of ground water in the remaining water-bearing units of the study region.

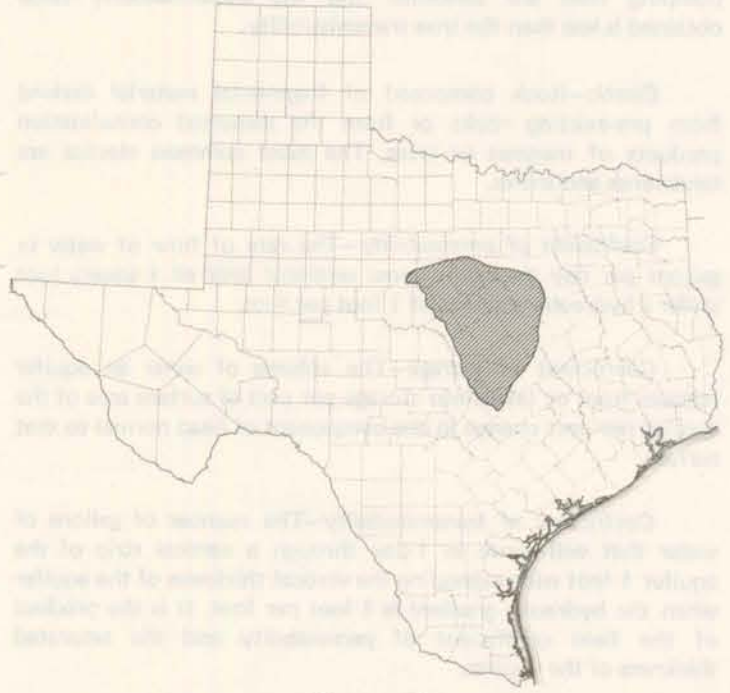

Figure 1

Location of Study Region

The general scope of this investigation included the collection, compilation, and analysis of data relating to ground water from the Antlers and Travis Peak Formations in central Texas, and the presentation of these data, results of analyses, recommendations, and conclusions in a published report. The report is prepared in two volumes. Volume 1 contains interpretive information presented as text and related figures and tables. Volume 2 contains supporting basic data including well location maps, records of wells, drillers' logs, and chemical analyses of water.

The scope, although directed toward the quantitative aspects of water availability, also includes collection and use of chemical quality data, surface and subsurface geological data, study of the magnitude and extent of contamination of ground water by oil-field brine in the northwest outcrop area, synthesis and analysis studies of aquifer hydrology using digital computer model techniques, and review of previous work by federal and State agencies.

Location and Extent

The study region has an areal extent of 13,888 square miles, and represents 5.02 percent of the State's total area. It is in the Brazos, Colorado, and Trinity River basins and includes all or parts of 20 counties—Bell, Bosque, Brown, Burnet, Callahan, Comanche, Coryell, Eastland, Erath, Falls, Hamilton, Hill, Lampasas, Limestone, McLennan, Milam, Mills, Somervell, Travis, and Williamson. Data were also used from the fringes of Ellis, Hood, Johnson, and Navarro Counties. Consideration was given to only that portion of each county in which usable ground water is found within the Antlers and Travis Peak Formations.

For the purpose of this report usable ground water is considered to be water which contains less than 3,000 milligrams per liter (mg/l) dissolved solids. However, it is recognized that ground water with higher dissolved-solids content is desalted and used in some areas.

Topography, Soils, and Vegetation

Most of the land surface expressions in the study region are the result of stream erosion of relatively flat or gently dipping rocks that are exposed on the surface. Along its southern and eastern edges, the region has gently rolling prairies with low relief and a well-developed, dendritic drainage. Soils consist of dark calcareous clays, sandy loams, and clay loams in the uplands, while dark gray to reddish-brown calcareous clay loams and clays are found in the bottomlands. Vegetation in the uplands consists of tall bunch grasses and scattered mesquite, while elm, hackberry, and pecan are usually found in the bottomlands.

In the northwest, the physical features consist of gently sloping prairies with moderate relief and mature dendritic drainage. The northeast has an irregular topography of high relief with erosional knobs, abrupt valleys, resistant outliers, and moderate to rapid surface drainage caused by major streams cutting across the various rock formations. Soils are usually light-colored, neutral to slightly acid sand, sandy loams, and loamy sands. Vegetation in the northwest and northeast part of the region consists mainly of tall bunch grasses, mesquite, cedar, and scrub oak.

The central part of the region has moderately high relief with tabular divides, small limestone-capped mesas, sharp-cut valleys, and a thorough dendritic drainage. The soils are dark, stony, shallow to deep calcareous clays in the uplands and reddish-brown to dark gray clay loams and clays in the bottomlands. Tall bunch grasses, scattered mesquite, some live oak, and cedar grow in the uplands while oak and juniper are usually found in the bottomlands.

Elevations range from 350 feet in the southeast to 2,200 feet above mean sea level in the northwest. Drainage is to the southeast by the Bosque, Brazos, Colorado, Lampasas, Leon, Navasota, and Paluxy Rivers and their tributaries.

Climate

The climate of the region covered by this report is characterized by long, hot summers and short, mild winters. The average minimum temperature for January, the coldest month, ranges from 32°F (0°C) in the northwest to 39°F (4°C) in the southeast. The average maximum temperature for July, the warmest month, is 96°F (36°C) throughout most of the study region. The annual mean free air temperature for the period 1931-60 ranged from 65°F (18°C) in the northwest to 68°F (20°C) in the east (Carr, 1967).

The average annual precipitation ranges from 24 inches in the northwest to 36 inches in the east. These figures are based on National Weather Service records for the 30-year period 1931-60, and are illustrated on Figure 2 along with average monthly precipitation for periods of record at selected stations.

The average annual gross lake-surface evaporation for the period 1940-65 ranged from 60 inches in the east to 80 inches in the northwest (Kane, 1967).

Population

In 1970, approximately 846,000 inhabitants lived within the region covered by this report. This represented about 7.5 percent of the State's population. More than 65 percent of the region's population lived in urban areas having 2,500 or more inhabitants. Some of the urban areas are the cities of Austin, Belton, Brownwood, Cameron, Copperas Cove, Georgetown, Hillsboro, Killeen, Lampasas, Marlin, Mexia, Stephenville, Taylor, Temple, and Waco. The remaining inhabitants lived in rural areas or smaller communities.

Economy

The principal manufacturing plants are in or near larger cities; however, some plants in smaller cities process local products, especially those related to agriculture. The cities of Waco and Temple are important manufacturing centers, while Austin, although having light industry, derives its economy mainly from the activities of State and federal governmental agencies. Killeen, another major city in the region, is the home of Fort Hood, the largest free world armored post.

Agriculture has contributed substantially to the economy of the region. In some parts, the development of ground water for irrigation has greatly increased the production of agricultural products and improved the standards of living on farms. Farming includes raising various grains, small garden and truck vegetables and fruits, peanuts, and various forms of livestock. Dairy farming is practiced throughout the region and is of local importance. Ranching consists of raising cattle, goats, hogs, and sheep and is especially important where farming is not predominant.

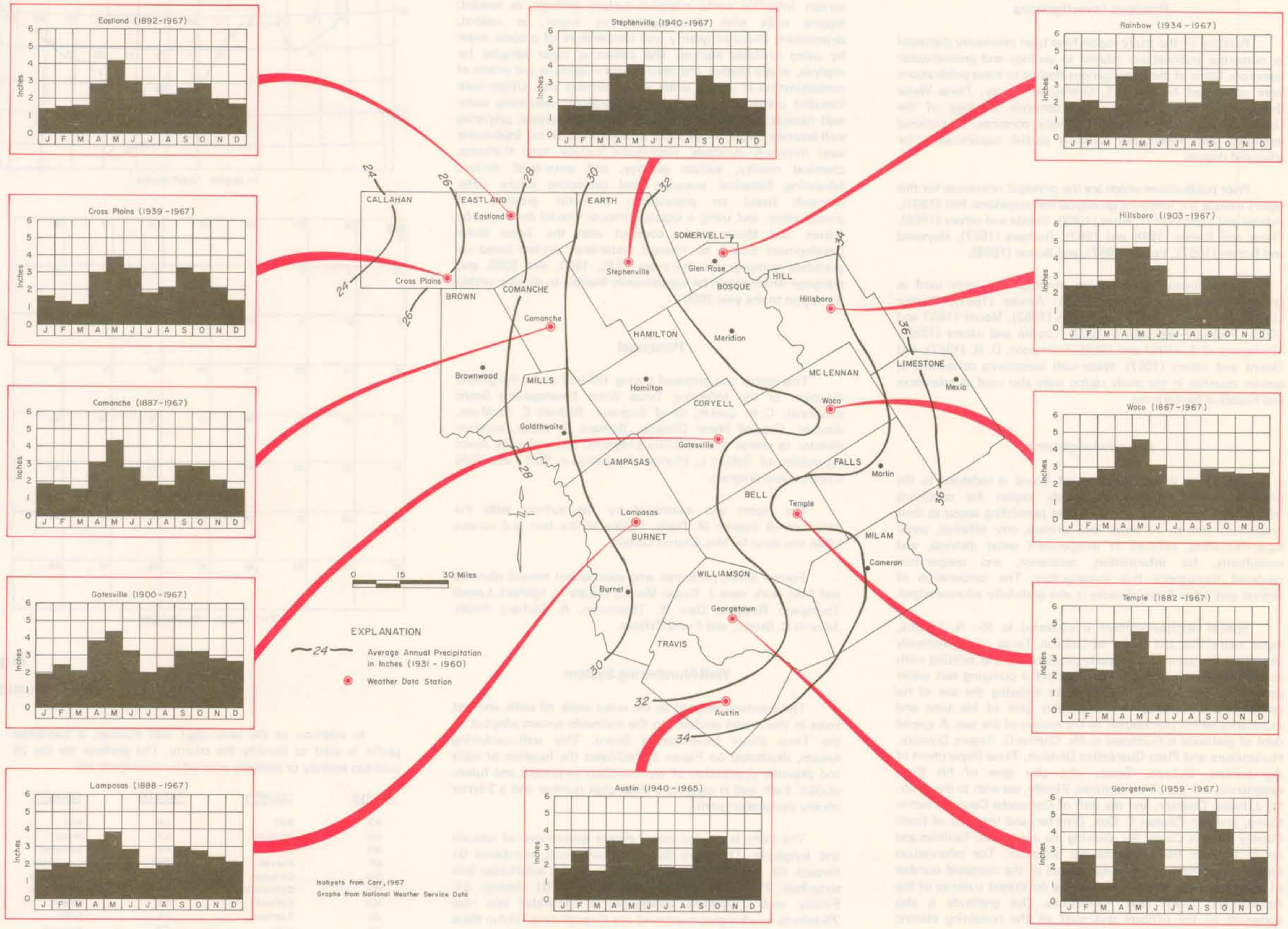

Figure 2

Average Annual Precipitation, 1931-60, and Average Monthly Precipitation for Period of Record at Selected Stations

Industrial activities include the operation of sand and gravel pits and stone quarries, the production of clay and manufacture of brick and tile products, the production of cement materials, and manufacture of cement. Lignite is mined in Milam County where it is used to produce electricity for the processing of aluminum ores shipped in from other states or imported from foreign countries.

Oil and natural gas and gas liquids (natural gasoline, butane, and propane) are produced in many counties. In these areas the supporting activities connected with the production of oil and gas further enhance the economy.

Previous Investigations

Portions of the study region have been previously discussed in numerous publications related to geology and ground-water resources. Some of the investigations leading to these publications were conducted by the U.S. Geological Survey, Texas Water Development Board, Bureau of Economic Geology of the University of Texas at Austin, private concerns, educational institutes, and individuals fulfilling partial requirements for advanced degrees.

Prior publications which are the principal references for this report include the following geological investigations: Hill (1901), Adkins and Lozo (1951), Atlee (1962), Rodda and others (1966), Fisher and Rodda (1966 and 1967), Rodgers (1967), Hayward and Brown (1967), Young (1967), and Boone (1968).

The following ground-water investigations were used as principal references: Follett (1956), Arnow (1957), Rayner (1959), Holloway (1961), Henningsen (1962), Mount (1962 and 1963), Peckham and others (1963), Cronin and others (1963), Thompson, G. L. (1967 and 1969), Thompson, D. R. (1967), and Mount and others (1967). Water-well inventories conducted in certain counties in the study region were also used as references and historical background.

Acknowledgements

The Texas Water Development Board is indebted to the property owners within the study region for supplying information concerning their wells and permitting access to their properties; and to all water well drillers, city officials, water superintendents, officials of independent water districts, and consultants, for information, assistance, and cooperation rendered throughout this investigation. The cooperation of federal and other State agencies is also gratefully acknowledged.

Special acknowledgment is extended to Mr. N. L. Box, water well driller and farmer of DeLeon, Texas, who generously permitted the use of his property, equipment, and existing wells in order that the Board might conduct a pumping test under water-table conditions. In addition to allowing the use of his property and facilities, Mr. Box also gave of his time and experience which contributed to the success of the test. A special debt of gratitude is expressed to Mr. Charles G. Rogers, Director, Horticulture and Plant Quarantine Division, Texas Department of Agriculture, DeLeon, Texas, who also gave of his time, experience, and use of lab facilities. Finally, we wish to thank Mr. W. J. Parks, Director, and the staff of Comanche County Electric Co-op, and Mr. Clinton C. Cox, Director, and the staff of Erath County Electric Co-op, for allowing the use of their facilities and access to their files on numerous occasions. The information obtained was necessary to keep abreast of the increased number of irrigation wells being drilled in the northwest outcrop of the Antlers and Travis Peak Formations. Our gratitude is also conveyed to the officers and staff of the remaining electric companies whose information was needed to have complete coverage of the northwest outcrop area.

Method of Investigation

The field work for this investigation was begun in September 1964 and ended in September 1968. The office work, assembling data and writing the report, was accomplished from September 1968 to September 1969. Some office work was done intermittently throughout the study during periods of inclement weather. The investigation procedure is presented in chronological order.

Field work consisted of conducting a complete inventory of the historical pumpage; collecting past and present water levels; collecting data on well construction, yields, pumping rates, and pumping levels; collecting drillers', electric, and various other logs and well completion data; examining sample cuttings; determining elevations of wells having water-level or stratigraphic data; conducting pumping tests on certain wells where construction details are known and power and yield tests on certain irrigation wells; mapping surface geology, as needed; logging wells with electric/gamma-ray logger, as needed; determining chemical quality and temperature of ground water by using available analyses and collecting water samples for analysis, where needed; and determining magnitude and extent of contamination of ground water in the outcrop area. Office work included constructing geologic cross-sections; tabulating water well records, logs, water levels, and chemical analyses; preparing well-location maps; constructing geologic maps of net fresh-water sand thickness, structure, piezometric surface, total thickness, chemical quality, surface geology, and water-level decline; tabulating historical pumpage and projecting future water demands based on population, economic growth, and precipitation; and using a digital computer model developed by Dames and Moore under contract with the Texas Water Development Board, to forecast water-level decline based on predicted pumpage for the years 1975, 1990, and 2020, and pumpage which would be economically feasible to develop within the region to the year 2020.

Personnel

This report was prepared during 1964-69 under the general direction of the following Texas Water Development Board personnel: C. R. Baskin, Chief Engineer; Richard C. Peckham, director, Ground Water Division; Bernard B. Baker, assistant director in charge of availability programs; and under the direct supervision of Robert L. Bluntzer, coordinator, East Texas field investigations program.

The report was assembled by the authors with the assistance of Eugene M. Davis. Typing of the text and various tables was done by Mrs. Sharon Colton.

Former Board personnel who contributed toward planning and field work were J. Russel Mount, Hillary H. Iglehart, Lowell Thompson Rodgers, Dale R. Thompson, A. Richard Smith, Johnnie B. Brown, and Frank Tribble.

Well-Numbering System

The numbers assigned to the water wells, oil wells, and test holes in this report conform to the statewide system adopted by the Texas Water Development Board. This well-numbering system, illustrated on Figure 3, facilitates the location of wells and prevents duplication of well numbers in present and future studies. Each well is assigned a seven-digit number and a 2-letter county designation prefix.

The State is divided into 1-degree quadrangles of latitude and longitude. There are 89 such quadrangles, numbered 01 through 89. Each 1-degree quadrangle is further subdivided into sixty-four 7½-minute quadrangles numbered 01 through 64. Finally, each 7½-minute quadrangle is subdivided into nine 2½-minute quadrangles, numbered one through nine. Within these 2½-minute quadrangles, each well is assigned a two-digit number beginning with 01.

The first two digits of each well number identify the 1-degree quadrangle; the third and fourth digits indicate the 7½-minute quadrangle; the fifth digit identifies the 2½-minute quadrangle; and the last two digits identify the well within the 2½-minute quadrangle.

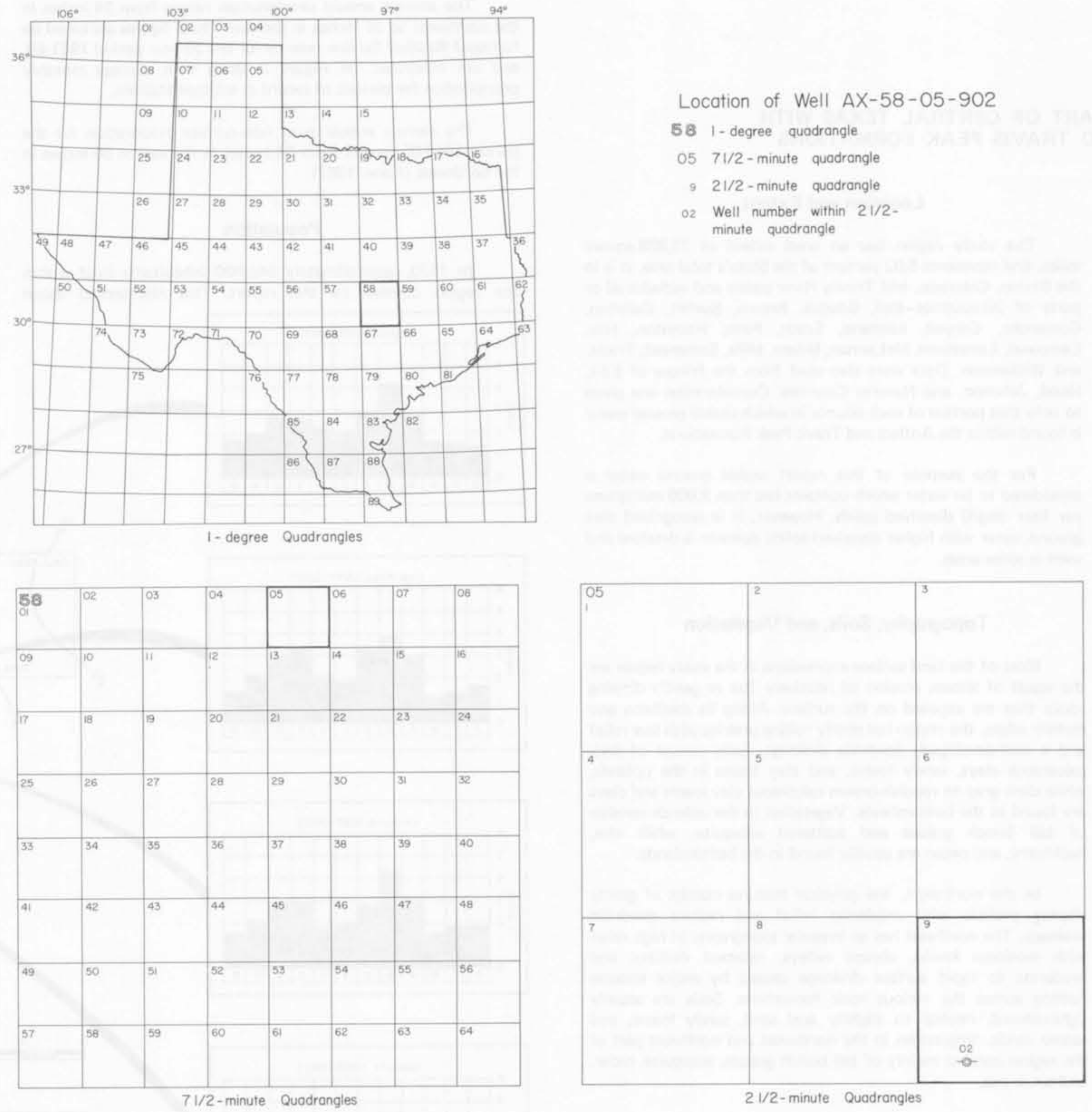

Figure 3
Well-Numbering System

In addition to the seven-digit well number, a two-letter prefix is used to identify the county. The prefixes for the 24 counties entirely or partially covered by this report are:

PREFIX	COUNTY	PREFIX	COUNTY
AX	Bell	LW	Hill
BB	Bosque	LY	Hood
BR	Brown	PX	Johnson
BT	Burnet	RW	Lampasas
BX	Callahan	SD	Limestone
DY	Comanche	ST	McLennan
HB	Coryell	TK	Milam
JD	Eastland	TL	Mills
JK	Ellis	TY	Navarro
JP	Erath	XJ	Somervell
JR	Falls	YD	Travis
LA	Hamilton	ZK	Williamson

Well AX-58-05-902, shown on Figure 3, is in Bell County (AX); 1-degree quadrangle 58; 7½-minute quadrangle 05; 2½-minute quadrangle 9; and was the second well inventoried in that 2½-minute quadrangle.

Definitions of Terms

This section is intended to acquaint the reader with some of the terms used in this report. Many of these definitions were selected from previous reports and from the Glossary of Geology and Related Sciences, American Geological Institute (1957).

Acre-foot—The volume of water required to cover 1 acre to a depth of 1 foot (43,560 cubic feet), or 325,851 gallons.

Acre-feet per year—One acre foot per year equals 892.13 gallons per day.

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

Aquifer—A formation, group of formations, or part of a formation that is water bearing.

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

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

Argillaceous—Applied to all rocks or substances composed of clay, slate, or shale. They are readily distinguished by the peculiar odor they emit when breathed on, known in mineralogy as the "argillaceous odor".

Artesian aquifer, confined aquifer—Artesian (confined) water occurs where an aquifer is overlain by rock of lower permeability (such as clay) that confines the water under pressure greater than atmospheric. The water level in an artesian well will rise above the top of the aquifer even without pumping.

Barrier effect—The result of a hydrologic boundary of restricted permeability which affects the radial growth of the cone of depression of a pumping well. This occurs after an elapsed pumping time. Because of this, the drawdown data of pumping tests are abnormal and the transmissibility value obtained is less than the true transmissibility.

Clastic—Rock composed of fragmental material derived from pre-existing rocks or from the dispersed consolidation products of magmas or lavas. The most common clastics are sandstones and shales.

Coefficient of permeability—The rate of flow of water in gallons per day through a cross sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot.

Coefficient of storage—The volume of water an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface.

Coefficient of transmissibility—The number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide extending the vertical thickness of the aquifer when the hydraulic gradient is 1 foot per foot. It is the product of the field coefficient of permeability and the saturated thickness of the aquifer.

Cone of depression—Depression of the water table or piezometric surface surrounding a discharging well, more or less the shape of an inverted cone.

Confining bed—One which, because of its position and its impermeability or low permeability relative to that of the aquifer, keeps the water in the aquifer under artesian pressure.

Contact—The place or surface where two different kinds of rock or geologic units come together, shown on both maps and cross-sections.

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

Dendritic drainage pattern—A pattern characterized by irregular branching in all directions with the tributaries joining the main stream at all angles.

Dip of rocks—The angle or amount of slope at which a bed is inclined from the horizontal; direction is also expressed (such as 1 degree, southeast; or 90 feet per mile, southeast).

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

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

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

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

Facies—The "aspect" belonging to a geological unit of sedimentation, including mineral composition, type of bedding, fossil content, etc. (such as sand facies). General appearance or nature of one part of a rock body as contrasted with other parts. A stratigraphic body as distinguished from other bodies of different appearance or composition.

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

Formation—A body of rock that is sufficiently homogeneous or distinctive to be regarded as a mappable unit, usually named from a locality where the formation is typical (such as Glen Rose, Paluxy, and Georgetown Formations).

Head, or hydrostatic pressure—The pressure exerted by the water at any given point in a body of water at rest reported in pounds per square inch or in feet of water. That of ground water is generally due to the weight of water at higher levels in the same zone of saturation.

Hydraulic gradient—The slope of the water table or piezometric surface, usually given in feet per mile.

Igneous rocks—Rocks formed by solidification from a molten or partially molten state.

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

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

Leaching—The process of removal of soluble material by passage of water through soil.

Lignite—A brownish-black coal in which the alteration of vegetal material has proceeded further than in peat but not so far as sub-bituminous coal.

Lithology—The description of rocks, usually from observation of hand specimen, or outcrop.

Metamorphic rocks—Rocks formed in the solid state due to pronounced changes of temperature, pressure, and chemical environment, which take place, in general, below the shells of weathering and cementation.

Million(s) gallons per day—One million gallons per day equals 3.068883 acre-feet per day or 1,120.14 acre-feet per year.

Mineral—Any chemical element or compound occurring naturally as a product of inorganic processes.

Nodes—The centers of the subareas (polygons) used to represent pumpage centers in the digital computer simulation of the Hensell and Hosston aquifers in the study region.

Outcrop—That part of a rock layer which appears at the land surface.

Milliequivalents per liter (me/l)—An expression of the concentration of chemical substances in terms of the reacting values of electrically charged particles, or ions, in solution. One milliequivalent per liter of a positively charged ion (such as Na^+) will react with 1 milliequivalent per liter of a negatively charged ion (such as Cl^-).

Milligrams per liter (mg/l)—One milligram per liter represents 1 milligram of solute in 1 liter of solution. As commonly measured and used, one milligram per liter is numerically equivalent to one part per million (1 milligram of solute in 1 kilogram of solution).

Perched ground water—Ground water separated from an underlying body of ground water by unsaturated rock. Its water table is a perched water table.

Percolation—The movement, under hydrostatic pressure, of water through the interstices of a rock or soil, except the movement through large openings such as caves.

Permeable—Pervious or having a texture that permits water to move through it perceptibly under the head differences ordinarily found in subsurface water. A permeable rock has communicating interstices of capillary or supercapillary size.

Permeability of an aquifer—The capacity of an aquifer for transmitting water under pressure.

Piezometric surface—An imaginary surface that everywhere coincides with the static level of the water in the aquifer. The surface to which the water from a given aquifer will rise under its full head.

Polygon—A subarea which resulted from segmenting the study region into smaller areas for the purpose of simulating the Hensell and Hosston aquifers using a digital computer.

Porosity—The ratio of the aggregate volume of interstices (openings) in a rock or soil to its total volume, usually stated as a percentage.

Recharge of ground water—The process by which water is absorbed and is added to the zone of saturation. Also used to designate the quantity of water that is added to the zone of saturation, usually given in acre-feet per year or in million gallons per day.

Rejected recharge—The natural discharge of ground water in the recharge area of an aquifer by springs, seeps, and evapotranspiration, which occurs when the rate of recharge exceeds the rate of transmission in the aquifer.

Resistivity (electrical log)—The resistance of the rocks and their fluid contents penetrated in a well to induced electrical currents. Permeable rocks containing fresh water have high resistivities.

Safe yield—The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate will become no longer economically feasible. The practical rate of withdrawing water from an underground reservoir perennially for human use.

Sedimentary rocks—Rocks formed by the accumulation of sediments in water or from air. The sediment may consist of rock fragments or particles of various sizes; of the remains or products or animals or plants; of the product of chemical action or evaporation; or of mixtures of these materials.

Specific capacity—The rate of yield of a well per unit of drawdown, usually expressed as gallons per minute per foot of drawdown. If the yield is 250 gallons per minute and the drawdown is 10 feet, the specific capacity is 25 gallons per minute per foot.

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

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

Strike of bed—The direction or bearing of a horizontal line in the plane of an inclined stratum. It is perpendicular to the direction of dip.

Structural feature, geologic—The result of the deformation or dislocation (such as faulting) of the rocks in the earth's crust. In a structural basin, the rock layers dip toward the center or axis of the basin. The structural basin may or may not coincide with a topographic basin.

Transit recharge—That portion of the actual recharge which is transmitted downdip to the areas of pumpage.

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

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

Water level, pumping—The water level during pumping measured in feet below the land surface.

Water level, static—The water level in an unpumped or nonflowing well measured in feet above or below the land surface or sea-level datum.

Water table—The upper surface of a zone of saturation except where the surface is formed by an impermeable body of rock.

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

Yield of a well—The rate of discharge, commonly expressed as gallons per minute, gallons per day, or gallons per hour.

GEOLOGY AS RELATED TO THE OCCURRENCE OF GROUND WATER

Geologic History

Precambrian

Precambrian rocks in central Texas were, in part, derived from great deposits of sediments consisting of limestone, sandstone, and carbonaceous shales. After these sediments were deposited, they were intruded by igneous magmas, metamorphosed, and folded. These igneous and metamorphic rocks were then extensively eroded before the start of the Paleozoic era.

Paleozoic

During most of the Paleozoic era, a sedimentary basin existed throughout much of central Texas which received sediments consisting of sandstone, limestone, carbonaceous shales, and other marine sediments. This basin received sediments until late Pennsylvanian time when the Llano Uplift and the Ouachita Fold Belt caused a regional tilting to the west and faulting in the immediate uplift area. During Permian time, the basin shifted to the west and only the extreme western part of central Texas received sediments, while the remainder of the area underwent extensive erosion.

Triassic and Jurassic

Extensive erosion continued throughout Triassic time in the central Texas area. However, during the Jurassic period, only the western and central part of the area had continued erosion, while the Jurassic sea, advancing from the east Texas basin, began inundating the extreme eastern part. Jurassic sediments possibly extend as far west as eastern McLennan County.

Cretaceous

At the beginning of the Cretaceous period, the sea advanced from the south and east and eventually covered all of central Texas. This major transgression, together with several minor regressions and a continuously oscillating shoreline, caused the present sequence of sediments. During late Cretaceous (Gulf Series), a general uplift occurred to the west and the Cretaceous sea started a general regression and covered only the eastern portion of central Texas. The uplift continued and the seas finally regressed to the south marking the end of the Cretaceous period in central Texas.

Tertiary and Quaternary

At the close of the Cretaceous period, noted by uplifting of the western area and subsidence of the coastal area, sediments of Tertiary and Quaternary age were deposited. The repeated transgression and regression of the sea resulted in an alternating sequence of marine and continental deposits. During the Tertiary period, the Balcones faulting occurred probably as a result of continued subsidence near the Gulf Coast and moderate uplift to the west. Since the beginning of the Tertiary period, most of the rocks in central Texas have been subjected to erosion and weathering thus producing the present topographic and geomorphic features.

Stratigraphy

The stratigraphic units that supply fresh to slightly saline water to wells in the study region range in age from Paleozoic to Recent. The most important water-bearing rocks in central Texas are of Cretaceous age.

The Cretaceous System is composed of two series, Gulf and Comanche, and each is divided into groups. The Gulf Series is divided into the following five groups: Navarro, Taylor, Austin, Eagle Ford, and Woodbine. The Comanche Series is divided into the following three groups: Washita, Fredericksburg, and Trinity.

The Navarro, Taylor, Austin, and Eagle Ford Groups consist predominantly of limestone, marl, and shale and yield only small amounts of water in localized areas. The Woodbine Group is the only important aquifer of the Gulf Series in the area covered by this report. It consists predominantly of sand and shale and is capable of yielding small to moderate amounts of water. The Woodbine Group is discussed in detail in the sections covering the stratigraphy of the water-bearing formations and the occurrence and availability of ground water.

The Washita, Fredericksburg, and Trinity Groups are the three major water-bearing units of the Comanche Series in the study region, and each of the three groups is divided into separate formations and members.

The Washita Group is divided into the Buda, Del Rio, and Georgetown Formations. The Buda and Del Rio are composed of limestone and shale, respectively, and neither is known to yield usable water in the region. The Georgetown consists of limestone and usually yields small amounts of water.

The Fredericksburg Group is divided into the Kiamichi, Edwards, Comanche Peak, and Walnut Formations. The Kiamichi is a shale and is not known to yield water in the region. The Edwards is composed of limestone, often porous, and in some areas yields large amounts of good quality water. The Comanche Peak and Walnut Formations consist of limestone and shale, and in some localized areas yield small amounts of water.

The Edwards and Georgetown Formations are usually hydrologically connected and in this report are discussed in detail as the Edwards and associated limestones.

The Trinity Group is the principal water-bearing group of rocks in the region and is divided into the Paluxy, Glen Rose, Travis Peak, and Antlers Formations. The Paluxy consists of sand and shale and is capable of yielding small to moderate amounts of water. The Glen Rose is predominantly a limestone and yields only small amounts of water. The Travis Peak is composed of limestone, sand, and shale. It is the principal water-bearing formation of Cretaceous age in the region and yields up to large amounts of good quality water. The Travis Peak Formation is divided into the following seven members: Hensell, Pearsall, Cow Creek, Hammett, Sligo, Sycamore, and Hosston. The name Antlers Formation is applied northwest of a line where the Glen Rose pinches out and the Paluxy and Travis Peak coalesce to form one unit.

The Paluxy, Glen Rose, Antlers, and Travis Peak Formations, including the members of the Travis Peak Formation, are discussed in detail in the sections covering the stratigraphy of the water-bearing formations and the occurrence and availability of ground water.

The relationship, approximate maximum thickness, brief description of lithology, and summary of water-bearing properties of the stratigraphic units are shown in Table 1. The outcrop areas of the various formations are illustrated on Figure 21. Altitude and depth of the formations and their total thicknesses and net sand thicknesses are shown on Figures 22 through 34, 50, and 53.

Geologic cross-sections are profiles portraying an interpretation of a vertical section of the earth. Six geologic cross-sections were constructed; four are dip sections, and two are strike sections. Dip sections are constructed approximately perpendicular to the strike of the beds and parallel to the dip of the beds, while strike sections are constructed parallel to the strike of the beds. These six geologic sections, illustrated on Figures 55 through 60, show the structure and stratigraphic relationships of the geologic units.

Structure

The structural features most affecting the Cretaceous aquifers in the area of study are the regional dip, the Balcones and Luling-Mexia-Talco Fault Zones, the Llano Uplift, the McGregor High, and the ridges and valleys of the eroded pre-Cretaceous depositional surface. The regional structure and generalized geologic outcrops are shown on Figure 4.

The Cretaceous rocks generally dip east-southeast at a rate of about 15 feet per mile in the northwest part of the study region, gradually increasing to approximately 40 feet per mile in the central part, and then rapidly increasing east of the fault zone to around 80 to 100 feet per mile.

The Balcones Fault Zone in the study region extends from Austin through Waco to Hill County. The Luling-Mexia-Talco Fault Zone parallels the Balcones on the east.

The Balcones Fault Zone has produced displacements up to 400 feet in McLennan County and perhaps as much as 600 feet in Travis County. The Luling-Mexia-Talco Fault Zone has displacements of 700 feet and more in some locations. These fault zones may completely block or severely restrict the

Table 1.—Stratigraphic Units and Their Water-Bearing Characteristics

SYSTEM	SERIES	GROUP	STRATIGRAPHIC UNITS	APPROXIMATE MAXIMUM THICKNESS (FEET)	CHARACTER OF ROCKS	WATER-BEARING CHARACTERISTICS
Quaternary and Tertiary				—	Mostly gravel, sand, silt, and clay	Yields small to large amounts of water
Cretaceous	Gulf	Navarro		550	Shale, marl, and sand	Locally yields small amounts of usable water
		Taylor		1,100	Marl and limy shale	
		Austin		600	Chalky limestone	
		Eagle Ford		300	Shale	Not known to yield water
		Woodbine		200	Ferruginous sand, sandstone, shale, sandy shale, clay, and some lignite and gypsum	Yields small to moderate amounts of water
	Comanche	Washita	Buda Formation	50	Limestone	Not known to yield water
			Del Rio Formation	100	Shale	Not known to yield water
			Georgetown Formation	150	Limestone	May yield water in connection with the Edwards
		Fredericksburg	Kiamichi Formation	50	Shale	Not known to yield water
			Edwards Formation	175	Hard, fossiliferous limestone (often honeycombed), reef material, shale, chert, and dolomite	Yields small to large amounts of water
			Comanche Peak Formation	150	Limestone and limy shale	Yields little or no water
			Walnut Formation	200	Shale and calcareous clay	Yields little or no water
		Trinity	Paluxy Formation	200	*Paluxy*: Fine to medium grained sand, shale sandy and calcareous shale, some pyrite, and iron nodules	*Paluxy*: Yields small to moderate amounts of water
			Glen Rose Formation	1,500	*Glen Rose*: Limestone, shale, and anhydrite	*Glen Rose*: Locally yields small amounts of usable water
			Antlers Formation	225	*Antlers*: Fine to coarse-grained sand with varicolored shale and streaks of limestone	*Antlers*: Yields small to moderate amounts of water
			Travis Peak Formation	1,800	Travis Peak Formation: *Hensell Member*, (Approximate maximum thickness 175 feet): Conglomerate, fine to coarse grained sand, sandstone, siltstone, shale sandy shale, clay, limy clay, and limestone	*Hensell*: Yields small to large amounts of water
					Pearsall Member, (Approximate maximum thickness 85 feet): Predominantly shale interbedded with sand; however, in the calcareous facies, the unit is composed almost entirely of calcareous sediments	*Pearsall*: Locally yields small amounts of water
					Cow Creek Member, (Approximate maximum thickness 130 feet): Limestone	*Cow Creek*: Yields small amounts of water near outcrop
					Hammett Member, (Approximate maximum thickness 140 feet): Shale	*Hammett*: Not known to yield water
					Hosston Member, (Approximate maximum thickness 1,550 feet): Conglomerate, fine to coarse sand and sandstone, siltstone, shale, sandy and calcareous shale, clay, and limestone	*Hosston*: Yields moderate to large amounts of water
					Sycamore Member: Sand and conglomerate with calcareous cement, shale, and limestone	*Sycamore*: Yields little or no water
					Sligo Member, (Approximate maximum thickness 130 feet): Limestone	*Sligo*: Not known to yield water
Pre-Cretaceous rocks				(?)	*Cotton Valley Group* (?): Possibly sands, conglomerate, and shale	The *Cotton Valley Group* of Jurassic age, if present, may yield usable water in the southeastern area (amount and quality unknown)
					Paleozoic rocks: Shale, limestone, dolomite, sandstone, evaporites, and metamorphic rock	*Paleozoic rocks* yield small to moderate amounts of usable water in western and northwestern areas

movement of ground water downdip and may contribute to contamination by allowing undesirable saline water to enter along fault planes; therefore, these two fault zones affect the occurrence, movement, and quality of the ground water in the study region. The western boundary of the Luling-Mexia-Talco Fault Zone appears to be the controlling factor in the downdip limit of fresh to slightly saline water occurring in the lower Cretaceous aquifers.

The Llano Uplift, a structural dome of igneous and metamorphic rocks, is centered in Llano County southwest of the study region. This dome acted as a source area for sediments, and affected the depositional environment of the Cretaceous rocks immediately east of the uplift area.

The McGregor High is an erosional high where non-deposition occurred during early Cretaceous time. This high is probably a Paleozoic limestone ridge or mesa that existed as an island during early Cretaceous time and was part of one of the ridges that occurs on the pre-Cretaceous surface. It is located in southwest McClennan County near the city of McGregor. As a result of this high, there is a marked decrease in the thickness of the lower Cretaceous rocks, particularly in the Hosston Member of the Travis Peak Formation; therefore, the movement of ground water through this area is restricted.

The various ridges and valleys that existed on the pre-Cretaceous surface had a direct effect on the lower Cretaceous sediments as they were being deposited on that irregular surface. Thicker accumulations of sand occur in the valleys and thinner accumulations on the ridges, thus influencing the occurrence and movement of ground water. The pre-Cretaceous surface, or base of the Antlers and Travis Peak Formations, is shown on Figure 22.

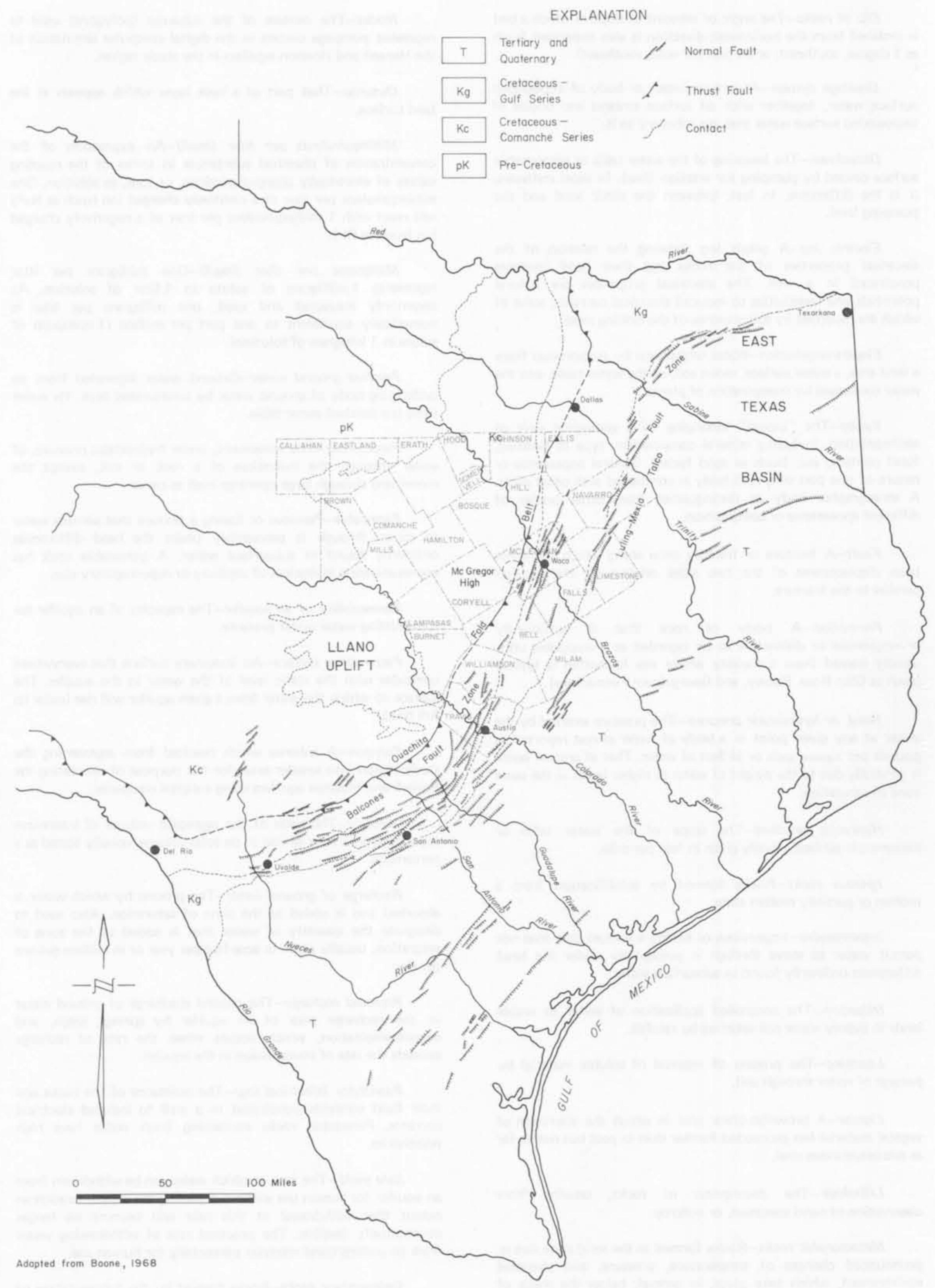

Figure 4

Regional Structure and Generalized Geologic Outcrops

STRATIGRAPHY OF THE WATER-BEARING FORMATIONS

Pre-Cretaceous Rocks

Paleozoic rocks crop out in the northwestern and western part of the study region in Brown, Burnet, Callahan, Comanche, Eastland, Erath, Lampasas, and Mills Counties (Figure 21). The occurrence of usable water in these rocks is generally limited to the outcrop area or the area adjacent to the outcrop.

Of the many Paleozoic rocks in the region, only the Ellenburger Group of Ordovician age, and rocks of Pennsylvanian age are considered important water producers.

The Ellenburger, in the outcrop area in Burnet and Lampasas Counties, consists of limestone and dolomite, both of which may have vugs and cavernous zones associated with joints and fractures, commonly enlarged by solution, and interbedded lenses and nodules of chert.

Rocks of Pennsylvanian age consist of conglomerate, sandstone, siltstone, limestone, shale, sandy shale, carbonaceous shale, coal beds, redbed facies of sandstone and shale, non-marine sandstone and shale, and channel-fill deposits consisting of gravel, sand, and clay. In the northwest part of the study region where they yield fresh water, these sediments regionally dip toward the west or northwest at an average rate of approximately 50 feet per mile, and are separated from the Trinity Group, of Cretaceous age, by an angular unconformity.

Jurassic rocks could possibly be represented by sands, conglomerates, and shales in the southeastern part of the study region. These rocks may yield potable water. The amounts and quality of water are unknown.

Antlers Formation

The Antlers Formation is a lateral equivalent of the Travis Peak and Paluxy Formations. It occurs in the northwest part of the region where the Glen Rose Formation thins and is no longer a traceable or distinguishable unit. There the clastic sand and clay of the Travis Peak and Paluxy Formations coalesce to form a single unit, the Antlers Formation (Figures 55 and 57).

The Antlers outcrops in Brown, Callahan, Comanche, and Eastland Counties. The Antlers dips to the southeast at an average rate of about 12 feet per mile, increasing slightly near its southeastern limit.

The lower part of the Antlers consists of pebbly conglomerate, fine to coarse-grained sand and sandstone (predominantly siliceous), and interbedded red to green sandy clay. The middle part is predominantly a red-brown, sandy clay interbedded with clayey sand and sandstone and a few streaks of limestone or calcareous siltstone. The upper part of the Antlers is composed of friable, compact, massively bedded, fine-grained sandstone with interbedded red-brown to gray-green sandy clay and clay.

The Antlers has been subjected to extensive erosion, therefore, a complete section is found in only a few places. One of these complete sections is the Spring Mesa location in Callahan County where the total thickness is 220 feet, as noted in oil test BX-30-46-901. In most of the outcrop area, the erosional remnant of the Antlers has a thickness of 100 feet or less, as illustrated on Figure 23.

Travis Peak Formation

The Travis Peak Formation outcrops in the northern, northwestern, and western part of the study region in Brown, Burnet, Comanche, Eastland, Erath, Hamilton, Hood, Lampasas, Mills, and Travis Counties. The Travis Peak overlies Paleozoic rocks throughout the region except in the extreme southeast where it possibly overlies Jurassic rocks. The Travis Peak underlies the Glen Rose Formation throughout the region. The lower sands and shales of the Travis Peak are geologically and hydrologically connected with the basal sands of the Antlers Formation. The Travis Peak in the subsurface extends throughout the study region east of the outcrop.

The Travis Peak Formation in much of the region is composed of a lower sand unit, a middle argillaceous unit, and an upper sand unit. The lower sand unit generally consists of sand and sandstone, conglomerate, shale, and clay, and is termed the Hosston Member. In the extreme downdip area, a limestone unit, the Sligo Member, overlies the Hosston as shown on Figure 55. The middle unit is predominantly a clay or shale, termed the Pearsall Member; in downdip areas where distinguishable carbonate (limestone) beds overlie the shale, the terms Cow Creek Member (limestone) and Hammett Member (shale) are used (Figure 55). The upper sand unit, termed the Hensell Member, consists of sand and sandstone, occasionally conglomerate, shale and clay, and some limestone.

This lithology generally occurs throughout the region except in the west-central part where a calcareous facies of the Travis Peak Formation exists. Here the various members of the Travis Peak can be differentiated in some areas; however, due to their calcareous characteristics and the lack of good subsurface data, they are generally undifferentiated and are referred to as the calcareous facies of the Travis Peak Formation. The calcareous facies occurs in Bell, Burnet, Brown, Coryell, Hamilton, Lampasas, Mills, and Williamson Counties as illustrated on Figure 23.

The calcareous facies of the Travis Peak Formation consists of a lower calcareous conglomeratic unit, a middle calcareous unit, and an upper calcareous clastic unit. The lower unit is a conglomerate consisting of limestone and dolomite pebbles with a calcareous cement and is named the Sycamore Member (equivalent to the Hosston Member). The middle unit is predominantly a limestone with varying amounts of argillaceous material and is probably equivalent to the Cow Creek Member; however, it is commonly referred to as the Pearsall Member and is so used in this report. The upper unit, equivalent to the Hensell Member, is composed of calcareous sand, silt and clay, and limestone.

Hosston Member

The Hosston Member is the lower sand unit of the Travis Peak Formation and is between the underlying Paleozoic rocks and the overlying Pearsall or Hammett Members. The Hosston exists as a distinguishable unit in essentially the entire study region east of the outcrop, except possibly in the west-central where the Sycamore Member is its equivalent. The Hosston is often referred to as the "Lower Trinity Sand" or the "Second Trinity" by drillers and residents in the region. The Hosston is the most important aquifer in the region.

The Hosston is composed of: pebbly, sandy conglomerate, generally poorly sorted, multicolored and cemented with calcite or opaline (silica) cement; fine- to very coarse-grained, poorly to well sorted sand and sandstone that is poorly to well cemented with calcite or less commonly with opaline cement, gray to tan through red-brown in color; sandy and silty clay with some waxy clay, gray, green, yellow, or brown color; various colored shale; and occasionally streaks of limestone. Crossbedding is commonly associated with the conglomeratic beds, and the sands range from thin bedded to massive. The sands and conglomerates are predominantly siliceous with the pebbles consisting of chert or quartz. The conglomeratic zones commonly occur at or near the base and decrease in abundance and frequency downdip. The clay and shale zones are interbedded and gradational vertically and laterally.

The thickness of the Hosston varies greatly in the study region with a maximum thickness of 1,555 feet occurring in well TK-59-01-301 in Milam County and a minimum thickness of 5 feet in the Round Mountain measured section, 6 miles northwest of Comanche. The thickness of the Hosston can be seen in the various geologic sections on Figures 55 through 60 and the thickness map on Figure 23.

The Hosston Member has a regional dip to the east in the northern, central, and western parts of the region and to the southeast in the area adjacent to and east of the Balcones Fault Zone. Locally the direction may vary due to the depositional structure and localized thickening or thinning of the Hosston. The regional dip and the local variations are illustrated on the geologic sections and on Figure 24 which shows the altitude and depth to the top of the Hosston Member, the major faults influencing the Hosston, and its downdip limit of fresh to slightly saline water.

Sligo Member

The Sligo Member of the Travis Peak Formation is the carbonate equivalent of the Hosston and exists in the subsurface in the southeastern part of the study region where the Hosston grades upward into a shale and then into limestone. The Sligo consists of fossiliferous, dolomitic limestone that is crystalline to chalky, occasionally sandy or shaly, and interbedded with shale. The Sligo ranges in thickness from 0 to 130 feet and is not known to yield water in the study region.

Pearsall Member

The Pearsall Member of the Travis Peak Formation comprises clastic rocks of the predominantly argillaceous middle unit. The Pearsall occurs when the limestones of the Cow Creek Member thin and gradually pinch out in a westward direction. As this occurs, the shales of the Cow Creek Member and the underlying shales of the Hammett Member coalesce to form the Pearsall Member as illustrated on Figure 57.

The Pearsall is present in the northern, central, and northwestern part of the study region, west of a line trending southwest through the west-central part of Hill County, extreme southeastern Bosque County, extreme northwestern McLennan County, and southeastern Coryell County; and is gradational into the calcareous facies of the Travis Peak Formation in western Bell County.

In this area the Pearsall is composed of clay, commonly silty to sandy, some of it waxy, green, maroon, red-brown, or gray in color, interbedded with lenses of sand. Occasionally streaks of limestone occur. The Pearsall in this area is commonly called "redbeds" by local drillers and farmers.

The Pearsall ranges in thickness from 0 to 85 feet and pinches out near the Antlers Formation. The Pearsall thickens downdip and has various areas of local thickening and thinning, which often occur with an opposite thickening or thinning of the Hosston. The Pearsall has approximately the same dip as the underlying Hosston.

Hammett Member

The Hammett Member is the lower part of the argillaceous middle unit of the Travis Peak Formation where it has a distinguishable upper carbonate (limestone) bed.

The Hammett is present in the northeastern, east-central, eastern, and southern parts of the study region, east of a line trending southwest through the west-central part of Hill County, extreme southeastern Bosque County, extreme northwestern McLennan County, southeastern Coryell County, and is gradational into the calcareous facies in western Bell County.

The Hammett is predominantly a shale, gray to buff in color, occasionally silty or sandy, with streaks of fossiliferous, dolomitic limestone particularly in the upper part. In areas where sandy zones occur, the Hammett may yield small amounts of water.

A maximum thickness of 140 feet is encountered in well JR-39-43-801 in extreme southeastern Falls County; however, the Hammett usually ranges from 40 to 75 feet thick. The dip of the Hammett generally corresponds with that of the Hosston.

Cow Creek Member

The Cow Creek Member is the upper carbonate (limestone) bed of the argillaceous middle unit of the Travis Peak Formation. It is a distinguishable unit in the northeastern, east-central, eastern, and southern parts of the study region. Since the Cow Creek is the controlling factor on the location of the Hammett, they have the same boundaries.

The Cow Creek is composed of limestone, cream to tan in color, fossiliferous, often sandy and dolomitic with the sand increasing westward particularly in the southern part, and is occasionally porous due to vugs and fractures.

The thickness of the Cow Creek ranges from 0 to 125 feet in the study region, with the maximum thickness recorded in well YD-58-25-901 in west-central Travis County. The Cow Creek gradually thins in a westward direction, eventually becoming indistinct with only a few limestone lenses present in the north and northwest. The average thickness of the Cow Creek ranges from 40 to 75 feet, with a thickness of 100 feet common in the south. The dip of the Cow Creek is approximately the same as the Hosston.

The Cow Creek may yield small amounts of water in the area near or adjacent to its outcrop.

Hensell Member

The Hensell Member is the upper sand unit of the Travis Peak Formation and is overlain by the Glen Rose Formation and underlain by the Pearsall or Cow Creek Member. The Hensell is distinguishable in the entire study region, except possibly in the west-central part where, due to the abundance of calcium carbonate (limestone) in the Hensell, a distinction between it and the underlying Cow Creek Member is very arbitrary. Included with the Hensell Member is the "Bluff Dale Sand," a term used by various authors for a clastic series immediately below the limestones of the Glen Rose Formation. The "Bluff Dale Sand" is generally considered time-equivalent to the lower Glen Rose. However, the "Bluff Dale Sand" is probably hydrologically connected with the Hensell Member and is included as part of the Hensell in this report. The Hensell is commonly referred to as the "First Trinity" or "Upper Trinity Sand" by local drillers, engineers, and residents. It is the second most important aquifer in the study region. Most domestic and livestock wells drilled to the Travis Peak Formation are completed in the Hensell.

The Hensell consists of: pebbly, sandy, multicolored conglomerate that is poorly sorted and poorly to well cemented with calcite, opaline cement, or clay; fine- to coarse-grained, gray, green, and buff to red-brown sand and sandstone that is poorly to well sorted, poorly to well cemented with calcite and occasionally with opaline cement, and often unconsolidated in the subsurface; sandy to silty, green, gray, red, yellow, or brown clay that is occasionally waxy and calcareous; gray to green shale; and lenses of limestone that are often arenaceous. The conglomerates are often crossbedded, and occasionally the sands are crossbedded although they usually range from thin-bedded to massive. The sands and conglomerates consist mainly of chert or quartz. The conglomerates usually occur near the base of the Hensell and are found only in the area near or immediately adjacent to the outcrop. With the grain size and amount of sand decreasing in a southeastward direction, the sands grade into silty and sandy shales in the southeastern subsurface. This facies change is illustrated on Figure 25, which also shows the altitude and depth to the top of the Hensell, and on the geologic sections, Figures 55 through 58.

In the northern, northwestern, and central areas and to the west of the Balcones Fault Zone, the Hensell has a regional dip to the east. In the area east of the fault zone, the Hensell dips to the southeast. Variations from the regional pattern occur locally. The general east and southeast dip of the Hensell and the increased rate of dip in the fault zone are illustrated on Figure 25.

The total thickness of the Hensell varies considerably in the study region. It is thickest in the northwest and thins to the southeast. A maximum thickness of 178 feet occurs in well JP-31-54-401 in west-central Erath County, and a minimum of about 20 feet occurs in numerous locations in the southeastern part of the region.

A general decrease in thickness to the east and southeast is illustrated on Figure 26, along with the various trends of thickening and thinning and the area of the facies change from sand to shale. The thickness of the Hensell and the facies change are also illustrated on the geologic sections, Figures 55 through 60.

Calcareous Facies of the Travis Peak Formation

The calcareous facies of the Travis Peak Formation exists only in the west-central part of the study region where the clastic and cementing materials of the Travis Peak Formation have a general calcareous composition. This calcareous characteristic exists in all the units of the Travis Peak, making differentiation into the various members difficult and arbitrary. Nevertheless, in some areas where sufficient subsurface data are available, a general distinction can be made with the Sycamore Member representing the lower unit, the Pearsall Member representing the middle unit, and the Hensell Member representing the upper unit. The exact limit or extent of the calcareous facies is arbitrary; however, the approximate location is shown on Figure 23.

The lower unit of the calcareous facies of the Travis Peak Formation is the Sycamore Member, which is equivalent to and correlates with the Hosston Member. The Sycamore consists of coarse conglomerates, medium- to coarse-grained sand, silt, clay, and limestone. The conglomerates consist chiefly of limestone and dolomite pebbles and cobbles derived from the Llano Uplift. These conglomerates are often very well cemented with calcium carbonate (limestone) and are very hard. The sands have some limestone and dolomite fragments but are chiefly siliceous with calcium carbonate cement. The silts and clays are calcareous and usually occur near the top. The Sycamore grades upward into a finer clastic and more calcareous material, and the contact or boundary between the Sycamore and the overlying, middle unit is indistinct.

The middle unit, which is commonly called the Pearsall Member, is composed almost entirely of calcareous sediments. These sediments are usually composed of limestone, often sandy and dolomitic, occasionally fossiliferous, crossbedded, and coarse-grained. Clay and shale occur in various locations, and in the southern part of the calcareous facies these are probably equivalent to the Hammett while the limestone is probably equivalent to the Cow Creek. However, this differentiation is not traceable over a large area and may only occur locally. The middle unit is gradational upward into a predominantly clastic upper unit.

The upper unit, usually correlated to the Hensell Member, is generally finer grained and contains few, if any, conglomerates. It consists of fine- to coarse-grained sand and sandstone, silt, clay, and some limestone. The sand is usually siliceous and generally cemented with calcium carbonate. The silts and clays contain an abundant amount of calcareous material, often as much as half, therefore constituting a marl or silty marl.

The total thickness of the calcareous facies of the Travis Peak Formation is illustrated on Figure 23. The minimum thickness recorded is 90 feet in well RW-41-54-702 in western Lampasas County near the outcrop, and a maximum thickness of 300 feet is noted in well ZK-58-09-501 on the western edge of Williamson County.

The calcareous facies dips in various directions—northeast, east, and southeast—often changing direction in a relatively short distance due to the influence of the Llano Uplift.

Glen Rose Formation

The Glen Rose Formation crops out in the northern, northwestern, western, central, and southwestern parts of the study region in Bell, Bosque, Brown, Burnet, Comanche, Coryell, Eastland, Erath, Hamilton, Hood, Johnson, Lampasas, Mills, Somervell, Travis, and Williamson Counties. The outcrop area is shown on Figure 21. The Glen Rose overlies the Travis Peak Formation and underlies the Paluxy Formation. The only exceptions are in parts of Burnet County, where the Travis Peak is absent due to nondeposition and the Glen Rose overlies the Paleozoic rocks, and east of the downdip extent of the Paluxy Formation, where the Glen Rose underlies the Walnut Formation.

The Glen Rose extends on the surface or in the subsurface through essentially the entire study region, except in portions of Brown, Callahan, Comanche, and Eastland Counties where the Glen Rose thins and is no longer traceable or distinguishable. In this area, the Glen Rose pinches out and the Paluxy and Travis Peak Formations coalesce to form the Antlers Formation. The Glen Rose pinch-out is illustrated on Figures 55 and 57.

The Glen Rose Formation is composed primarily of limestone with some shale, sandy shale, clay, sandstone, and anhydrite. The limestone is often dense, finely crystalline, fossiliferous, and gray to tan in color, with marl and chalky limestone common.

From a featheredge near May in Brown County and northwest of Twin Mountains in Erath County, the Glen Rose gradually thickens southeastward and has a maximum thickness of 1,110 feet in Limestone County. The increase in thickness and general rate of dip are illustrated on Figures 55 through 60.

The Glen Rose produces fresh to slightly saline water in localized areas on or adjacent to its outcrop usually to small domestic and livestock wells. Away from the outcrop, water in the Glen Rose is highly mineralized and constitutes a potential source of contamination to wells completed in the underlying Travis Peak Formation.

Paluxy Formation

The Paluxy Formation extends on the surface or in the subsurface through the northern, western, and central parts of the study region. It crops out in Bell, Bosque, Brown, Burnet, Comanche, Coryell, Eastland, Erath, Hamilton, Hood, Johnson, Lampasas, Mills, Somervell, Travis, and Williamson Counties as shown on Figure 21. The Paluxy is overlain by the Walnut Formation and underlain by the Glen Rose Formation.

The Paluxy is composed predominantly of fine-grained, compact, friable, white quartz sand, ranging from very fine- to medium-grained and interbedded with sandy, silty, calcareous, or waxy clay and shale. The clay and shale are commonly dark and contain organic material. The sands are usually well sorted, poorly cemented, and crossbedded. Pyrite and iron nodules are often associated with the sands and frequently contribute a red stain to the individual beds. Some lenses and thin beds of limestone and marl occur locally.

The dip of the Paluxy is generally eastward with minor local variations as shown on Figure 27 which also shows the altitude of and depth to the top of the Paluxy.

The thickness of the Paluxy varies considerably in the study region. From a maximum thickness of 210 feet in the Twin Mountain measured section in northwestern Erath County, the Paluxy thins to the south and southeast. A complete pinch-out occurs along a line running from west of Hubbard through Waco and McGregor, west of Belton, through northwestern Williamson County, and through the extreme northwestern corner of Travis County. This thickness change is shown on the geologic sections and on Figure 28. Figure 28 also shows the approximate total thickness and the approximate downdip extent of the Paluxy Formation.

The Paluxy Formation is an important aquifer in the northern and central areas of the region and yields small to moderate amounts of water.

Edwards and Associated Limestones

The Edwards and associated limestones is the term used in this report for the water-bearing unit that includes the Georgetown and Edwards Formations. These two formations are hydrologically connected over most of the area and are seldom differentiated by drillers in the area; therefore, the term Edwards and associated limestones is used. The Comanche Peak Formation is not included because it is not known to yield significant amounts of water in the study region.

The Edwards and associated limestones supply small to large amounts of water to wells and constitute an important aquifer in the area south of the Lampasas River in Bell County and along and east of the Balcones Fault Zone. The Edwards crops out in this area paralleling the fault zone in Bell, Travis, and Williamson Counties as illustrated on Figure 29. It crops out in other areas usually as isolated outliers. The Edwards is present in Bell County north of the Lampasas River, but is not an important aquifer.

The Georgetown Formation is composed of a nodular limestone, usually white and massive, interbedded with layers of marl or marly shale. It is fossiliferous, commonly burrowed with fossil fragments found in the burrows, and abundant in pyrite.

The Edwards Formation consists of a hard, fossilferous limestone, thick-bedded to massive, and commonly dolomitic; reef material consisting of shell fragments and rudistid reefs; calcareous shale and marl; and bedded and nodular chert, flint, and dolomite.

In the Edwards and associated limestones, the limestone and dolomite beds are commonly extensively honeycombed and cavernous with numerous fractures and solution channels occurring within the individual beds. The dolomitic beds commonly have a sugary texture and often are misinterpreted as sandstone or sandy limestone by many drillers.

The total thickness of the Edwards and associated limestones ranges from 180 to 250 feet in the area of the study region where fresh to slightly saline water occurs in the aquifer. The thickness increases southward as illustrated on Figure 30.

The regional dip is to the east-southeast at an average rate of 80 feet per mile. This direction and rate is determined on the top of the Georgetown Formation which is the top of the Edwards and associated limestones. (See Figures 29 and 56.)

Woodbine Group

The sand facies of the Woodbine Group crops out in the northeastern part of the study region in Hill and northern McLennan Counties as illustrated on Figure 21. The Woodbine is overlain by the Eagle Ford Group and underlain by the Washita Group.

The Woodbine Group occurs as a sand facies and a shale facies. The sand facies is located in the northeastern area and is the water-bearing unit of the Woodbine; therefore, only the sand facies was mapped. The sand-shale facies line is shown on Figure 31, and the facies change as well as the shale facies itself are shown on Figures 55, 56, 57, 58, and 60. The areal extent of the sand facies of the Woodbine Group, both on the surface and in the subsurface, covers only the northeastern part of the region and is illustrated on Figure 31. The shale facies of the Woodbine is present in the eastern and southern parts, south of Waco and generally east of the fault zone. The shale facies gradually thins southward and is difficult to distinguish in the southern part of the region.

The Woodbine, in the northeastern part of the region, is composed of ferruginous, friable, fine-grained sand and sandstone that is locally indurated; black, usually noncalcareous interbedded shale and sandy shale; and laminated clay. The upper part of the Woodbine shows a vertical increase in shale and clay with gypsum, gypsiferous shale and clay, and lignite. The sands and sandstones thin southward, grading into sandy shales and shale. The Woodbine generally thickens to the northeast and thins to the south and southwest as illustrated on Figure 32, which shows the total thickness of the Woodbine Group.

The regional dip is to the east-southeast at an average rate of 33 feet per mile in the area west of the fault zone in Hill County, increasing to 50 feet per mile in the vicinity of the fault zone and to 67 feet per mile near Hubbard in southeastern Hill County. (See Figures 31 and 58.)

The Woodbine is an important aquifer in the northeastern area, especially in Hill County where it supplies water to many domestic and livestock wells and to wells in several small towns. The Woodbine can be expected to yield small to moderate amounts of water.

GENERAL GROUND-WATER HYDROLOGY

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. Many courses that the water may take to complete the hydrologic cycle are illustrated on Figure 5. Water occuring in the study region is derived, for the most part, from water vapor carried inland from the Gulf of Mexico.

Source and Occurrence

The primary source of ground water in the study region is the infiltration of precipitation either directly in the outcrop area or indirectly as seepage from streamflow. A large percentage of precipitation is evaporated back to the atmosphere directly or is consumed by plants and returned to the atmosphere by transpiration. A large portion also becomes surface runoff because it moves rapidly over land surfaces which are steep or impermeable. If the rain is intense, surface runoff increases because the time available for absorption is inadequate even in sandy areas. A small amount of the rainfall will percolate downward under the force of gravity to the zone of saturation where all the rock voids contain water. The upper surface of the zone of saturation is the water table. Water percolating down may be intercepted by a local impermeable layer of rock above the zone of saturation, thus forming a saturation zone above the main water table known as a perched water table. Two characteristics of fundamental importance in the zone of saturation are porosity, or the amount of the interstices, voids, or 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 generally have high porosity; however, because of their small voids they have little or no permeability and consequently do not readily transmit water. Sand and gravel are usually porous and permeable, the degree depending upon the size, shape, sorting, and amount of cementation of the grains. In limestone or igneous rocks, or in tightly cemented or compacted rocks, porosity and permeability are controlled to some degree by the occurrence and extent of joints, crevices, and solution cavities. For a formation to be an aquifer, it must be porous, permeable, water-bearing, and yield water in usable quantities.

Water in an aquifer is either under water-table or artesian conditions. In the outcrop area, ground water generally occurs under water-table, or unconfined conditions; it is under atmospheric pressure and will rise or fall in response to changes in the volume of water stored. In a well penetrating an unconfined aquifer, water will rise to the level of the water table. The hydraulic gradient in an unconfined aquifer coincides with the slope of the water table which corresponds to the general slope of the land surface.

Downdip from the outcrop or recharge area, ground water within an aquifer occurs under artesian or confined conditions as a result of being overlain by relatively impermeable beds which confine the water under a pressure greater than atmospheric. In a well penetrating an artesian aquifer, water will rise above the confining bed and, if the pressure head is large enough to cause the water in the well to rise above the land surface, the well will flow. The level or surface to which water will rise in an artesian well is called the piezometric surface. The hydraulic gradient of an artesian aquifer is the slope of the piezometric surface.

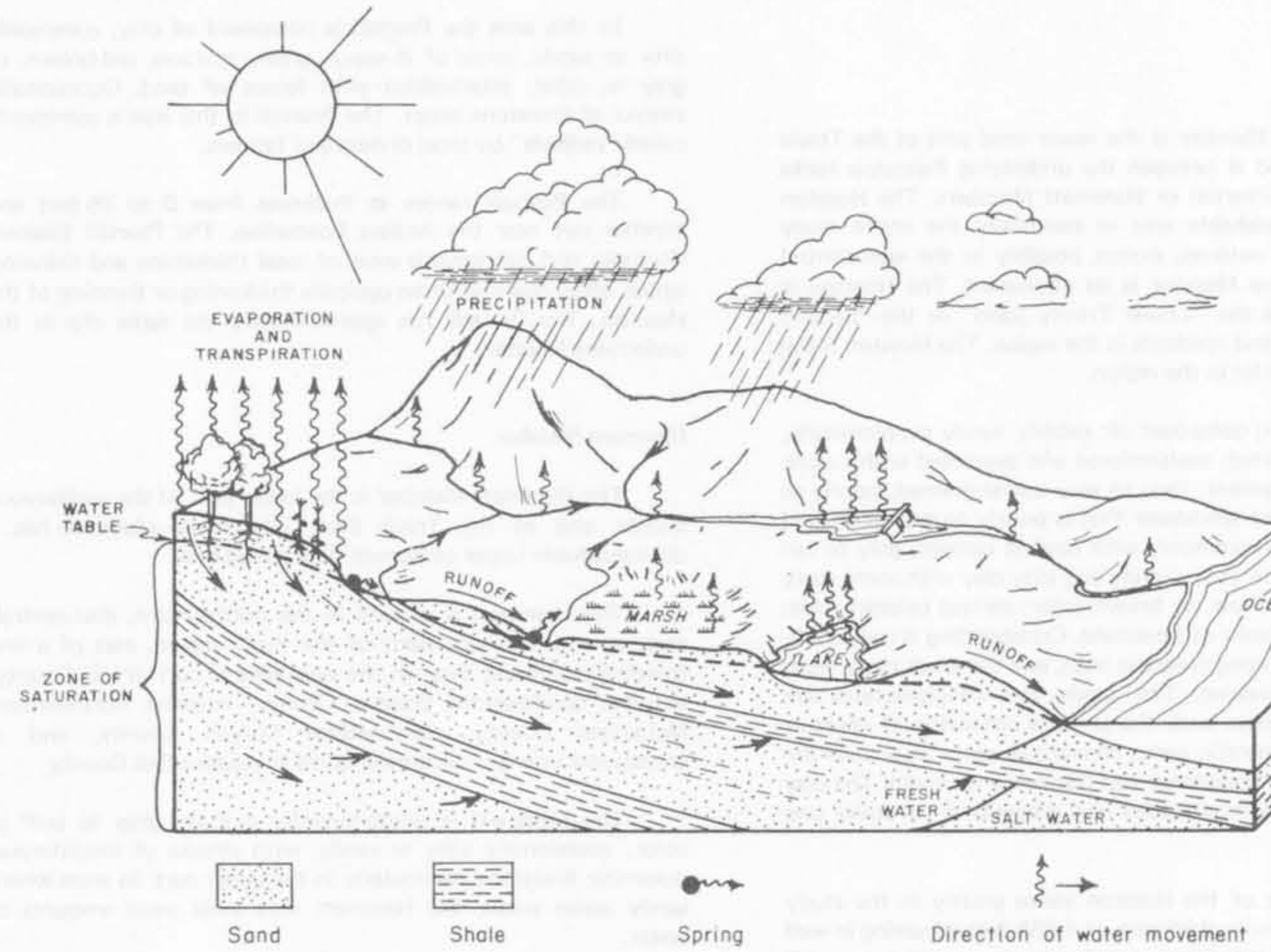

Figure 5
The Hydrologic Cycle

Recharge, Movement, and Discharge

Recharge is the process by which water is added to an aquifer and may result from either natural or artificial processes. Precipitation on the outcrop of an aquifer is generally the most significant natural source of recharge; however, water may enter from surface streams and lakes on the outcrop and possibly through intraformational leakage. Artificial recharge is the process of replenishing ground water in an aquifer and may be accomplished by (1) injection wells, and (2) infiltration of irrigation water or properly treated industrial waste water and sewage. The amount of recharge must be considered in determining the amount of water which can be safely developed from an aquifer, because it must balance the discharge over a long period of time or the water in storage in the aquifer will eventually be depleted. Factors which influence the amount of recharge received by an aquifer in its outcrop area are the amount and frequency of precipitation, rate of evaporation, types and condition of soil cover, topography, type and amount of vegetation, and the extent of the outcrop area. In addition, the ability of the aquifer to accept recharge and transmit it to areas of discharge influences the amount of recharge it will eventually receive. Recharge is generally greater during winter months when plant growth and well use are at a minimum and evaporation rates are low.

Ground water moves in response to the hydraulic gradient from areas of recharge to areas of discharge, or from points of higher hydraulic head to points of lower hydraulic head. Ground water under artesian conditions generally moves in the direction of the aquifer's regional dip, while movement of ground water under water-table conditions is closely related to the slope of the land surface. However, in areas of large and extensive withdrawals, ground water moves from all directions toward the areas of pumpage or lowered pressure. The rate of movement of ground water is directly related to the porosity and permeability of the aquifer. In most sands and gravels, the rate of movement ranges from tenths of a foot per day to many feet per year, while in cavernous gypsum or limestone, water flows in subterranean channels and may have velocities and volumes comparable to surface streams.

Discharge is a process by which water is removed from an aquifer and may be either natural or artificial. Natural discharge includes springs, effluent seepage to streams, lakes, and marshes which intersect the water table, transpiration by vegetation, evaporation through the soil where the water table is close to the land surface, and intraformational leakage as a result of differences in head. Since ground water moves in response to gravity, its natural discharge from an aquifer is always at a lower elevation than that of the recharge area. Ground water is artificially discharged from flowing and pumped water wells, and by drainage ditches, gravel pits, and other forms of excavation that intersect the water table.

Hydraulic Characteristics

When a well is pumped or allowed to flow, the level of the water table or piezometric surface is lowered; the difference between the discharging level and static level (water level before pumping or allowing to flow) is the drawdown. When water is discharged from an aquifer through a well, a hydraulic gradient toward the well is established and the water table or piezometric surface surrounding the well assumes the shape of an inverted cone which is called the cone of depression.

The water-producing capabilities of an aquifer depend upon the aquifer's ability to store and transmit water. Although the porosity of a rock is a measure of its capacity to store water, not all of this water may be recovered by pumping. Some of the water stored in the interstices is retained because of molecular attraction of the rock particles for water. Formulas have been developed to show the relationship of the yield of a well, the shape and extent of the cone of depression, and the properties of the aquifer including specific yield and coefficients of storage, transmissibility, and permeability. These formulas indicate that, within limits, the discharge from a well varies directly with the drawdown, that is, doubling the drawdown will nearly double the amount of discharge. The discharge per unit of drawdown (gallons per minute per foot), or specific capacity, is of value in estimating the probable yield of a well and the required pump setting. However, the type of well construction and thoroughness of well development also affect the well's specific capacity.

The coefficient of storage is the volume of water, in cubic feet, that will be released from or taken into storage by a vertical column of the aquifer having a base one foot square when the water level, or hydrostatic pressure, is lowered or raised one foot. When ground water is withdrawn from an artesian aquifer, the hydrostatic pressure is lowered and the weight of the overlying sediments compress the aquifer causing the water to be released from storage. The coefficient of storage in an artesian aquifer is small compared to that in a water-table aquifer; therefore, a discharging artesian well develops a cone of depression over a wide area in a short time. In a water-table aquifer, the coefficient of storage is much larger since it reflects the removal of water from storage by gravity drainage; therefore, under these conditions, it is essentially equal to the specific yield. The specific yield is the quantity of water that an aquifer will yield by gravity if it is first saturated and then allowed to drain; the ratio, expressed in percentage, of the volume of water drained to the volume of the aquifer that is drained.

The coefficient of transmissibility is the amount of water, in gallons per day, that will pass through a vertical strip of the aquifer one foot wide extending through the full saturated vertical thickness of the aquifer at a hydraulic gradient of one foot per foot and at the prevailing temperature of the water. The coefficient of transmissibility is an index to an aquifer's ability to transmit water.

The coefficient of permeability is defined as the quantity of water in gallons per day that will pass through a section of the aquifer one foot square under a hydraulic gradient of one foot per foot. It may be determined by dividing the coefficient of transmissibility by the saturated thickness of the aquifer, in feet.

The coefficients of storage and transmissibility of an aquifer are determined from pumping tests, which consist of pumping a well at a constant rate for a period of time and 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 and used in computing the effects that pumping will have on water levels in an aquifer at various times and at various distances from a pumped well. In addition to providing a means for computing the quantity of water that will flow through a given section of the aquifer, the coefficients can also be used in estimating the availability of ground water in storage.

Fluctuations of Water Levels

Water levels in wells fluctuate in response to natural and artificial factors acting on the aquifers, some of which are of regional significance while others are only local. In general, the major factors that control changes in water levels are the rates of recharge to and discharge from an aquifer.

Fluctuations due to natural factors generally occur daily and seasonally. Daily fluctuations are generally in response to barometric pressure, tidal effects, earthquakes, or changes in the rate of evapotranspiration. The magnitude of these fluctuations is usually very small. Seasonal fluctuations are generally the result of changes in the amount of precipitation and evapotranspiration on the aquifer's outcrop area which affects its recharge. During periods of drought, recharge is reduced and some of the water discharged from the aquifer must be withdrawn from storage. This causes water levels to decline. However, when adequate rainfall resumes, the volume of water drained from storage may be replaced and water levels will rise accordingly.

When a well is pumped, water levels in the vicinity are drawn down in the shape of an inverted cone with its apex at the pumped well. The development or growth of this cone depends on the aquifer's coefficients of transmissibility and storage, and on the rate of pumping. As pumping continues, the cone expands until it intercepts a source of replenishment capable of supplying sufficient water to satisfy the pumping 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 water pumped, the growth of the cone will cease and new balances between recharge and discharge are achieved. In areas where recharge or salvageable natural discharge is less than the amount of water pumped 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, each well superimposes its own individual cone of depression on that of neighboring wells. This results in the development of a regional cone of depression. When the cone of one well overlaps the cone of another, interference and an additional lowering of water levels occur 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 pumping from each well, the spacing between wells, and the hydraulic characteristics of the aquifer in which the wells are completed.

In water-table aquifers, water-level fluctuations due to pumping are generally less pronounced than in artesian aquifers; the water-level declines are the result of a decrease in storage. In artesian aquifers, water levels fluctuate primarily from an increase or decrease in pressure; the change in the amount of water in storage may be small even though the change in water level may be great.

CHEMICAL QUALITY OF GROUND WATER AS RELATED TO USE

General Chemical Quality of Ground Water

All ground water contains minerals carried in solution, the type and concentration of which depend upon the environment, movement, and source of the ground water. Precipitation is relatively free of minerals until it comes in contact with the various constituents which make up the soils and component rocks of the aquifer; then, as a result of the solvent power of water, minerals are dissolved and carried into solution as the water passes through the aquifer. The concentration depends upon the solubility of the minerals present, the length of time the water is in contact with the rocks, and the amount of dissolved carbon dioxide in the water. In addition, concentrations of dissolved minerals in ground water generally increase with depth and especially increase where circulation has been restricted due to faulting or zones of lower permeability. Restricted circulation retards the flushing action of fresh water moving through the aquifers, causing the water to become highly mineralized. In addition to natural mineralization, man can adversely alter the chemical quality of ground water by permitting highly mineralized water to enter fresh-water strata through inadequately constructed wells, by seepage from brine disposal pits used in disposing of highly mineralized water produced with oil, and by disposal of animal wastes, sewage, or various industrial waste into fresh-water strata or into aquifer recharge areas.

The principal chemical constituents found in ground water are calcium, magnesium, sodium, potassium, iron, silica, bicarbonate, carbonate, sulfate, chloride, and minor amounts of manganese, nitrate, fluoride, and boron. Concentrations of these ions or chemical constituents are commonly reported in milligrams per liter (mg/l). Milligrams per liter are the preferred metric system units and may be considered equal to parts per million at concentrations less than about 7,000 mg/l. At higher concentrations the units are not directly interchangeable, as conversion must take into account the greater differences in density of saline waters. The source, significance, and range of mineral constituents and properties of natural waters for the various aquifers in the study region are given in Table 2. Chemical analyses of water from selected wells in the study region are given in Volume 2 of this report.

Table 2.—Source, Significance, and Concentration of Dissolved-Mineral Constituents and Properties of Water

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

Only analyses which were representative of native ground water were used. Analyses are in milligrams per liter except percent sodium, specific conductance, pH, and SAR.

CONSTITUENT OR PROPERTY	SOURCE OR CAUSE	SIGNIFICANCE	RANGE IN CONCENTRATIONS, BY AQUIFER						
			TRAVIS PEAK[1]	TRAVIS PEAK -ANTLERS[2]	TRAVIS PEAK[3] HENSELL	TRAVIS PEAK[3] HOSSTON	PALUXY	EDWARDS AND ASSOCIATED LIMESTONES	WOODBINE
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 mg/l. High concentrations, as much as 100 mg/l, generally occur in highly alkaline water.	Forms hard scale in pipes and boilers. Carried over in steam of high pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type water softeners.	5 - 26	10 - 40	3 - 17	0 - 29	7 - 21	8 - 27	7 - 100
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment.	On exposure to air, iron in ground water oxidizes to reddish-brown precipitate. More than about 0.3 mg/l stain laundry and utensils reddish-brown. Objectionable for food processing, textile processing, beverages, ice manufacture, brewing, and other processes. U.S. Public Health Service (1962) drinking water standards state that iron should not exceed 0.3 mg/l. Larger quantities cause unpleasant taste and favor growth of iron bacteria.	.03- 2	.02- 1.4	.02- 2.2	0 - 3.6	.02- 16.8	0 - 7.4	.02- 2.5
Calcium (Ca) and Magnesium (Mg)	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quanitites in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.	(Ca) 27 - 136 (Mg) 8 - 96	(Ca) 30 - 174 (Mg) 2 - 82	(Ca) 1 - 98 (Mg) 1 - 47	(Ca) 1 - 102 (Mg) 0 - 78	(Ca) .6 - 204 (Mg) .4 - 78	(Ca) 10 - 110 (Mg) 3 - 33	(Ca) 1.5 - 226 (Mg) 0 - 16
Sodium (Na) and Potassium (K)[4]	Dissolved from practically all rocks and soils. Found also in oil-field brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.	9 - 806	3 - 330	11 - 520	9 - 632	13 - 740	5 - 650	23 -1,000
Bicarbonate (HCO_3) and Carbonate (CO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon-dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.	(HCO_3) 280 - 534	(HCO_3) 128 - 472	(HCO_3) 262 - 500	(HCO_3) 247 - 650	(HCO_3) 206 - 640	(HCO_3) 294 - 560	(HCO_3) 23 - 924
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. U.S. Public Health Service (1962) drinking water standards recommend that the sulfate content should not exceed 250 mg/l.	11 - 700	9 - 130	24 - 510	20 - 900	0 -1,140	6.8 - 549	47 - 670
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in oil-field brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. U.S. Public Health Service (1962) drinking water standards recommend that the chloride content should not exceed 250 mg/l.	15 - 530	3 - 217	11 - 334	16 - 528	10 - 179	10 - 489	21 - 550
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils. Added to many waters by fluoridation of municipal supplies.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth, depending on the concentration of fluoride, the age of the child, amount of drinking water consumed, and susceptibility of the individual (Maier, 1950, p. 1120-1132.)	.1 - 4.4	0 - 2.4	.1 - 6	0 - 5.3	.1 - 8.4	.1 - 8	.2 - 4.7
Nitrate (NO_3)	Decaying organic matter, sewage, fertilizers, and nitrates in soil.	Concentration much greater than the local average may suggest pollution. U.S. Public Health Service (1962) drinking water standards suggest a limit of 45 mg/l. Waters of high nitrate content have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding (Maxcy, 1950, p. 271). Nitrate shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.	0 - 168	0 - 70	0 - 64	0 - 20	0 - 70	0 - 36	0 - 11
Boron (B)	A minor constituent of rocks and of natural waters.	An excessive boron content will make water unsuitable for irrigation. Wilcox (1955, p. 11) indicated that a boron concentration of as much as 1.0 mg/l is permissible for irrigating sensitive crops; as much as 2.0 mg/l for semitolerant crops; and as much as 3.0 mg/l for tolerant crops. Crops sensitive to boron include most deciduous fruit and nut trees and navy beans; semitolerant crops include most small grains, potatoes and some other vegetables, and cotton; and tolerant crops include alfalfa, most root vegetables, and the date palm.	—	.06- .4	.4	0 - 6	0 - 1	0 - 2.2	0 - 2.5
Dissolved solids[5]	Chiefly mineral constituents dissolved from rocks and soils.	U.S. Public Health Service (1962) drinking water standards recommend that waters containing more than 500 mg/l dissolved solids not be used if other less mineralized supplies are available. For many purposes the dissolved-solids content is a major limitation on the use of water. A general classification of water based on dissolved-solids content, in mg/l, is as follows (Winslow and Kister, 1956, p. 5): Waters containing less than 1,000 mg/l of dissolved solids are considered fresh; 1,000 to 3,000 mg/l, slightly saline; 3,000 to 10,000 mg/l, moderately saline; 10,000 to 35,000 mg/l, very saline; and more than 35,000 mg/l, brine.	372 -2,280	182 - 980	311 -1,470	362 -1,885	289 -2,420	310 -1,848	162 -2,662

Table 2.—Source, Significance, and Concentration of Dissolved-Mineral Constituents and Properties of Water—Continued

CONSTITUENT OR PROPERTY	SOURCE OR CAUSE	SIGNIFICANCE	RANGE IN CONCENTRATIONS, BY AQUIFER						
			TRAVIS PEAK[1]	TRAVIS PEAK -ANTLERS[2]	TRAVIS PEAK[3] HENSELL	HOSSTON	PALUXY	EDWARDS AND ASSOCIATED LIMESTONES	WOODBINE
Hardness at $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All of the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. Waters of hardness up to 60 mg/l are considered soft; 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; more than 180 mg/l, very hard.	98 - 546	98 - 550	3 - 398	5 - 500	3 - 830	37 - 372	4 - 690
Percent Sodium (% Na)	Sodium in water.	A ratio (using milliquivalents per liter) of the sodium ions to the total sodium, calcium, and magnesium ions. A sodium percentage exceeding 50 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.	5 - 95	4 - 64	7 - 98	5 - 99	8 - 99	3 - 96	22 - 99
Specific conductance (micromhos at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.	643 - 3,760	300 - 1,550	554 - 2,464	632 - 3,840	488 - 3,330	342 - 2,940	255 - 4,032
Hydrogen ion concentration (pH)	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals.	7.0 - 8.1	6.7 - 7.9	7.4 - 9.1	7.3 - 8.9	6.8 - 8.9	6.9 - 8.5	5.5 - 8.5
Sodium-adsorption ratio (SAR)	Sodium in water.	A ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with soil (U.S. Salinity Laboratory Staff, 1954, p. 72, 156). Defined by the following equation: $SAR = \frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$, where Na^+, Ca^{++}, and Mg^{++} represent the concentrations in milliequivalents per liter (me/l) of the respective ions.	.2 - 35.4	.1 - 7.1	.3 - 32	.2 - 50	.3 - 56	.2 - 31	1.2 - 94

1/ Area within calcareous facies of the Travis Peak Formation. Area includes all or part of the following counties: Bell, Brown, Burnet, Coryell, Hamilton, Lampasas, Mills, and Williamson.
2/ Area where Travis Peak and Antlers Formations outcrop and adjacent counties. Most high capacity wells are completed in the Hensell and Hosston Members of the Travis Peak Formation. Area includes all or part of the following counties: Brown, Callahan, Comanche, Eastland, Erath, and Hamilton.
3/ Includes all of project area except that which is within the calcareous facies of the Travis Peak Formation. All wells considered are completed in "only" the Hensell or Hosston Members of the Travis Peak Formation.
4/ Sodium and potassium calculated as sodium (Na) is shown in the aquifer tabulations
5/ Recalculated values of dissolved solids are shown in the aquifer tabulations.

Public Supply and Domestic and Livestock

The U.S. Public Health Service (1962, p. 7-8) has established, and periodically revised, standards of drinking water to be used on common carriers engaged in interstate commerce. The standards are designed to protect the traveling public and may be used to evaluate public and domestic water supplies. Some of these standards, in milligrams per liter, are as follows:

SUBSTANCE	MAXIMUM CONCENTRATION RECOMMENDED (MG/L)
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 (FLUORIDE CONCENTRATIONS IN MG/L) 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

Optimum fluoride concentrations in drinking water depend upon climatic conditions,, because the quantity of water and consequently the amount of fluoride ingested is influenced primarily by air temperature. Use of drinking water having a fluoride content exceeding the upper recommended limits may cause mottling of the teeth of children (Dean, Dixon, and Cohen, 1935, p. 424-442). However, the use of drinking water that contains the optimum fluoride concentration appears to reduce the incidence of tooth decay (Dean, Arnold, and Elvove, 1942, p. 1,115-1,179 and Maier, 1950, p. 1,120-1,132).

The above limits are desirable for public and domestic use. However, many supplies which cannot meet these standards must be used for lack of a more suitable supply, and have been used for long periods of time without any apparent ill effects on the user.

In areas where the nitrate content of water is excessive, a potential danger exists. Concentrations of nitrate in excess of 45 mg/l in water used for infant feeding have been related to the incidence of infant cyanosis (methemoglobinemia or "blue baby" disease), a reduction of the oxygen content in the blood constituting a form of asphyxia (Maxcy, 1950, p. 271). Since nitrates are considered to be the final oxidation product of nitrogenous material, their presence in concentrations of more than a few milligrams per liter may indicate present or past contamination by sewage or other organic matter (Lohr and Love, 1954, p. 10). Excessive concentrations of iron and manganese in water cause reddish-brown or dark gray precipitates that stain clothes and plumbing fixtures. Water having a chloride content exceeding 250 mg/l may have a salty taste, and sulfate in excess of 250 mg/l may produce a laxative effect.

The hardness in water is caused principally by the concentration of calcium and magnesium. Excessive hardness of water causes an increase in soap consumption and encrustation and formation of scale in hot water heaters, water pipes, and cooking utensils. The hardness of water becomes objectionable when it exceeds 100 mg/l (Hem, 1959, p. 147). A commonly accepted classification of water hardness is shown in the following table.

HARDNESS RANGE (MG/L)	CLASSIFICATION	USABILITY
60 or less	Soft	Suitable for many uses without further softening
61 to 120	Moderately hard	Usable except in some industrial applications
121 to 180	Hard	Softening required by some industries
More than 180	Very hard	Softening desirable for most purposes

The total dissolved-solids content is a major limiting factor in the use of water. The following general classification of water is based on dissolved solids (Winslow and Kister, 1956, p. 5).

DESCRIPTION	DISSOLVED-SOLIDS CONTENT (MG/L)
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very Saline	10,000 to 35,000
Brine	More than 35,000

Quality limits for livestock are variable. The limits of tolerance depend principally on the kind of animal and, according to Heller (1933, p. 22), the total amount of soluble salts in the drinking water, more so than the kind of salt, is the important factor. According to Hem (1959, p. 241), a high proportion of sodium or magnesium and sulfate in highly mineralized waters would make them very undesirable for livestock use. Heller also suggests that as a safety rule 15,000 mg/l dissolved-solids content should be considered the upper limit for most of the more common livestock animals. According to Hem (1959, p. 241), the California State Water Pollution Control Board (1952) quotes other investigators who have found concentrations as high as 15,000 mg/l to be safe for limited periods but not for continuous use. In a publication (1950) relating to practices in Western Australia, the officers of the Department of Agriculture of that state quote the following upper limits for dissolved-solids concentration in livestock water (Hem, 1959, p. 241).

ANIMAL	DISSOLVED SOLIDS (MG/L)
Poultry	2,860
Pigs	4,290
Horses	6,435
Cattle (dairy)	7,150
Cattle (beef)	10,000
Adult sheep	12,900

Irrigation

The chemical composition of ground water is important in determining its usefulness for irrigation in that it should not adversely affect the productivity of the land. The extent to which chemical quality limits the suitability of ground water for irrigation depends on the nature, composition, and drainage of the soil and subsoil; the amounts of water used and methods of application; the kinds of crops grown; and the climate of the region, including the amounts and distribution of rainfall.

The most important characteristics in determining the quality of ground water for irrigation, according to the U.S. Salinity Laboratory Staff (1954, p. 69) are (1) total concentration of soluble salts; (2) relative proportion of sodium to other cations; and (3) concentration of boron or other elements that may be toxic.

High concentrations of dissolved salts in irrigation water may cause a buildup of salts in the soil solution and may make the soil saline. Increased salinity of the soil may drastically reduce crop yields by decreasing the ability of the plants to take up water and essential plant nutrients from the soil solution. The tendency of irrigation water to cause a high buildup of salts in the soil is called the salinity hazard of the water. The specific conductance of the water is used as an index of the salinity hazard.

High concentrations of sodium relative to the concentrations of calcium and magnesium in irrigation water may adversely affect soil structure. Cations in the soil solution become fixed on the surface of the soil particles; calcium and magnesium tend to flocculate the particles, whereas sodium tends to deflocculate the colloidal soil particles. Consequently, soils may become plastic, movement of water through the soil can be restricted, drainage problems can develop, and cultivation can be rendered difficult. This adverse effect on soil structure caused by high sodium concentrations in an irrigation water is called the sodium hazard. An index used for predicting the sodium hazard is the sodium-adsorption ratio (SAR), which is defined by the equation given in Table 2.

The U.S. Salinity Laboratory Staff (1954, p. 69-82) has prepared a classification diagram for irrigation waters in terms of salinity and sodium hazards. This diagram, reproduced in modified form as Figure 14, uses SAR and specific conductance in classifying irrigation waters. With respect to both the salinity and sodium hazards, waters are divided into four classes: low, medium, high, and very high. The classification range encompasses those waters which can be used for irrigation of most crops on most soils as well as those generally unsuitable for irrigation.

Boron is necessary for plant growth, but is highly toxic and unsuitable for irrigation at concentrations only slightly more than optimum. Scofield (1936, p. 286) suggests the following permissible limits of boron for irrigation water:

CLASSES OF WATER RATING	GRADE	SENSITIVE CROPS (MG/L)	SEMITOLERANT CROPS (MG/L)	TOLERANT CROPS (MG/L)
1	Excellent	<0.33	<0.67	<1.00
2	Good	.33 to .67	.67 to 1.33	1.00 to 2.00
3	Permissible	.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	Unsuit-	>1.25	>2.50	>3.75

Industrial

The chemical quality of water suitable for industry is not necessarily referenced to potability and may or may not be acceptable for human consumption. The tolerance in chemical quality of water for industrial use differs widely for different industries and different processes. Suggested water-quality tolerances for a number of industries are presented in Table 3 (American Water Works Association, 1950, p. 66-67). Water used by industry may be classified into three principal categories: cooling water, boiler water, and process water.

Cooling water usually is selected on the basis of temperature and chemical quality since any characteristic which may adversely affect the heat exchange surface is undesirable. Chemical substances such as calcium, magnesium, aluminum, iron iron, and silica may cause the formation of scale. Excessive hardness is objectionable because it contributes to the formation of scale in steam boilers, pipes, water heaters, radiators, and various other equipment where water is heated, evaporated, or treated with alkaline materials. The accumulation of scale increases costs for fuel, labor, repairs and replacement, and lowers the quality of many products. Some calcium hardness may be desirable because calcium carbonate sometimes forms protective coatings on pipes and other equipment and reduces corrosion. A high concentration of dissolved solids in a water may be closely associated with its corrosive properties, especially if chloride, calcium, magnesium chloride, sodium chloride in the presence of magnesium, acids, and oxygen and carbon dioxide are among the substances. Water that contains a high concentration of magnesium chloride may be highly corrosive because the hydrolysis of this salt yields hydrochloric acid.

Water used for boilers generally must meet rigid chemical-quality standards, especially in high-pressure boilers where the problems of encrustation and corrosion are greatly intensified. Iron oxides in boiler water may cause priming and foaming and magnesium chloride to break down and form hydrochloric acid. In addition, magnesium, calcium, and silica in most waters cause scale, and in the case of silica, the tendency for forming scale intensifies with increased boiler pressure. Suggested water-quality tolerances for boiler water (Moore, 1940, p. 263), in milligrams per liter for various pressures in pounds per square inch (psi), are as follows:

CONSTITUENT OR PROPERTY	0-150 PSI	150-250 PSI	250-400 PSI	OVER 400 PSI
Turbidity	20	10	5	1
Color	80	40	5	2
Oxygen consumed	15	10	4	3
Dissolved oxygen*	1.4	.14	.0	.0
Hydrogen sulfide (H_2S)	5**	3**	0	0
Total hardness as $CaCO_3$	80	40	10	2
Sulfate-carbonate ratio (Na_2SO_4:Na_2CO_3)	1:1	2:1	3:1	3:1
Aluminum oxide (Al_2O_3)	5	.5	.05	.01
Silica (SiO_2)	40	20	5	1
Bicarbonate (HCO_3)*	50	30	5	0
Carbonate (CO_3)	200	100	40	20
Hydroxide (OH)	50	40	30	15
Total dissolved solids***	3,000-500	2,500-500	1,500-100	50
pH value (minimum)	8.0	8.4	9.0	9.6

* Limits applicable only to water entering boiler, not to original water supply.
** Except when odor in live steam would be objectionable.
*** Depends on design of boiler.

Some treatment of boiler water may be needed, and it may be better to appraise the water source from the viewpoint of suitability for treatment rather than for direct use of raw water.

Process water is that water which is incorporated into or comes in contact with final manufactured products and is subject to a wide range of quality standards, usually rigidly controlled since they involve physical, chemical, and biological factors. In textile manufacturing, water used must generally be low in dissolved-solids content and free of iron and manganese which cause staining. The paper industry, especially where high grade paper is made, requires water in which all heavy metals are either absent or in small concentrations, and water approaching the quality of distilled water is required for the manufacture of pharmaceuticals. Water free of iron, manganese, and organic substances is generally required by many beverage industries. Unlike cooling and boiler water, much of the process water is consumed or undergoes a change in quality in the manufacturing process and generally is not available for reuse.

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

[Allowable Limits in Milligrams Per Liter Except as Indicated]

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

1 American Water Works Association, 1950.
2 A–No corrosiveness; B–No slime formation; C–Conformance to Federal drinking water standards necessary; D-NaCl, 275 mg/l.
3 Waters with algae and hydrogen sulfide odors are most unsuitable for air conditioning.
4 Some hardness desirable.
5 Water for distilling must meet the same general requirements as for brewing (gin and spirits mashing water of light-beer quality; whiskey mashing water of dark-beer quality).
6 Clear, odorless, sterile water for syrup and carbonization. Water consistent in character. Most high quality filtered municipal water not satisfactory for beverages.
7 Hard candy requires pH of 7.0 or greater, as low value favors inversion of sucrose, causing sticky product.
8 Control of corrosiveness is necessary as is also control of organisms, such as sulfur and iron bacteria, which tend to form slimes.
9 Ca $(HCO_3)_2$ particularly troublesome. Mg $(HCO_3)_2$ tends to greenish color. CO_2 assists to prevent cracking. Sulfates and chlorides of Ca, Mg, Na should each be less than 300 mg/l (white butts).
10 Uniformity of composition and temperature desirable. Iron objectionable as cellulose adsorbs iron from dilute solutions. Manganese very objectionable, clogs pipelines and is oxidized to permanganates by chlorine, causing reddish color.
11 Excessive iron, manganese, or turbidity creates spots and discoloration in tanning of hides and leather goods.
12 Constant composition; residual alumina 0.5 mg/l.
13 Calcium, magnesium, iron, manganese, suspended matter, and soluable organic matter may be objectionable.

OCCURRENCE AND AVAILABILITY OF GROUND WATER

Antlers and Travis Peak Formations

Source and Occurrence

The primary source of ground water in the Antlers and Travis Peak Formations is rainfall on the outcrop area. This area receives approximately 30 inches of rainfall annually. Surface-water seepage from lakes and streams, such as Proctor Lake and Lake Travis and the Lampasas, Leon, and Sabana Rivers located on the outcrop, are also a source of ground water to the Antlers and Travis Peak Formations. Another source of water is seepage from unlined earthen ponds and the effluent water used in the irrigation of crops on the outcrop.

Ground water in the Antlers Formation usually occurs under water-table conditions, while ground water in the Hensell and Hosston Members of the Travis Peak Formation occurs under both water-table and artesian conditions.

The lower sands and shales of the Travis Peak are geologically and hydraulically continuous with the basal sands of the Antlers. Both formations have a common piezometric surface and the same quality of water.

In the outcrop area, the sands and gravels of the Antlers and Travis Peak Formations are not completely water saturated, and water-table conditions prevail. This is illustrated by Figures 40 and 41 which delineate the areas where the Hensell and Hosston Members of the Travis Peak Formation are not completely water saturated. Ground water found in one area of the outcrop may not be found in another due to localized sand and shale facies as well as channel-like sand bodies characteristic of the Antlers and Travis Peak Formations. In addition, perched water tables and artesian conditions occur locally in the outcrop area due to sand lenses interbedded with shales within the Antlers and Travis Peak.

Artesian conditions exist downdip as a result of the Hensell and Hosston aquifers being overlain by the Glen Rose Formation and the Pearsall Member of the Travis Peak Formation. The aquifers here are completely water saturated, and the hydrostatic pressure is great enough to cause static water levels to rise above the aquifers and, in some cases, cause flowing wells. In the past, before the aquifers attained their present state of development, the piezometric surface was above the ground at the lower elevations downdip from the outcrop area. In these places, water wells drilled into the the Travis Peak Formation flowed. Later, overdevelopment caused water levels in some areas to decline more than 300 feet below land surface in places where flowing wells had previously existed. A few flowing wells can still be found in Bell, Falls, McLennan, Milam, and Travis Counties. Most of these wells are supplied from the Hosston Member of the Travis Peak Formation.

Recharge, Movement, and Discharge

Recharge to the Antlers and Travis Peak Formations occurs in the outcrop area which covers 1,732 square miles, or approximately 1,108,400 acres. In the northwest part of the study region, the outcrop soils generally consist of permeable sand and sandy clay loams. The terrain is characterized by gently sloping plains with moderate relief. These conditions are excellent for recharge from rainfall, seepage from streams and lakes, and infiltration resulting from the irrigation of crops. The amount of actual recharge to the Antlers and Travis Peak has not been determined, but the hydrographs on Figure 6 indicate that recharge does occur in the outcrop.

For the purpose of computer simulation of the Travis Peak Formation, an estimate of 3 percent of the average annual precipitation, as applied to the outcrop area, is assumed available as recharge. This is approximately 0.1 foot per year and amounts to 110,840 acre-feet per year that is available as recharge to the entire Antlers and Travis Peak Formations including the calcareous facies. However, due to small streams dissecting the formations and preventing downdip movement of the ground water, this amount is reduced to about 88,400 acre-feet per year. After subtracting the 1966 municipal, industrial, and irrigation pumpage that occurs shortly downdip from the dissecting streams, a net amount of approximately 82,400 acre-feet is available to move downdip in the Travis Peak Formation. Much of this available recharge is lost by natural rejection (springs, seeps, and evapotranspiration).

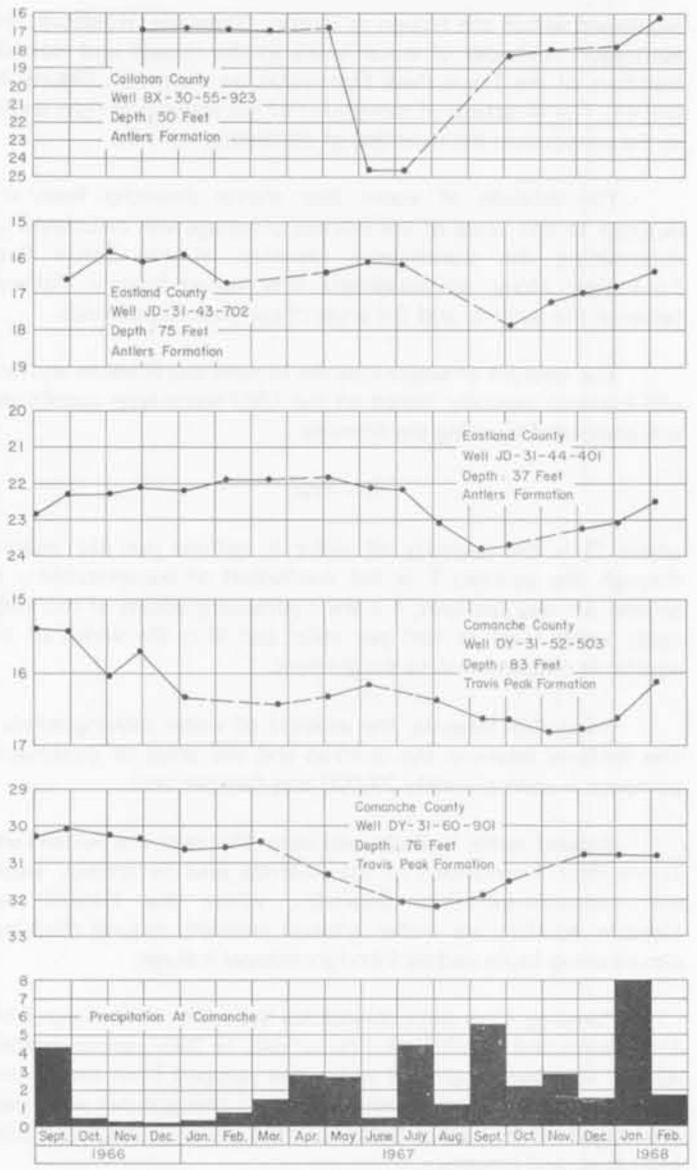

Figure 6
Hydrographs of Water Levels in Wells Completed in the Antlers and Travis Peak Formations Under Water-Table Conditions, and Monthly Precipitation at Comanche, Texas

In Burnet, Lampasas, Mills, and Brown Counties, the subsurface units of the Travis Peak Formation are well cemented and the outcrop soils are tight, reddish-brown clay loams and sandy clays. The terrain consists of tabular divides, small limestone-capped mesas, and valleys of moderate relief. These conditions suggest that there is comparatively little recharge in this area.

Ground water in the Antlers and Travis Peak Formations moves slowly downdip. Water-level measurements indicate the present gradient of the piezometric surface is 10 to 25 feet per mile east-southeast in most of the region.

In areas of continuous pumping, the direction of ground-water movement is toward these points of discharge from all directions. A major, elongated cone of depression has formed as a result of ground-water pumpage from the Hensell and Hosston aquifers in Bell, Coryell, Hill, McLennan, and Williamson Counties. The long axis of the cone parallels Interstate Highway 35 where well fields of municipalities and industries draw large supplies of ground water from the aquifers. The deepest part of the cone is at Waco, and smaller depressions have developed within the trough at Belton, Gatesville, Hillsboro, and McGregor. Altitudes of water levels in the Hensell and Hosston Members of the Travis Peak Formation are shown on Figures 40 and 41. The direction of movement of the water is at right angles to the contours in the direction of decreasing altitude.

The amount of water that moves downdip from the outcrop to the areas of continuous pumpage was calculated by determining the transmissive capacity of the Travis Peak Formation along an imaginary line approximately halfway between the outcrop and the areas of continuous pumpage.

The amount of water that the Hensell and Hosston aquifers will transmit annually, based on the 1967 water-level conditions, was computed by using the formula

$$Q = TIW,$$

where Q is the quantity of water in gallons per day moving through the aquifer; T is the coefficient of transmissibility in gallons per day per foot; I is the hydraulic gradient of the 1967 static water level in feet per mile; and W is the width of the aquifer in miles normal to the gradient.

Using this formula, the amount of water moving across a line halfway between the outcrop and the areas of continuous pumpage is approximately 23,000 acre-feet per year.

Ground water is discharged naturally from the Antlers and Travis Peak Formations in the outcrop area by springs, seeps, and evapotranspiration. Downdip, where the Hensell and Hosston aquifers are under artesian pressure, natural discharge occurs along faults and by intraformational leakage.

Pumping from wells constitutes the artificial discharge from the Antlers and Travis Peak Formations. In 1967, approximately 42,500 acre-feet of ground water was pumped from the Antlers and Travis Peak in the region. Most of this ground water was discharged from well fields of the various municipalities, industries, and irrigators.

Hydraulic Characteristics

The aquifer coefficients of transmissibility, permeability, and storage for the Travis Peak Formation are shown in Table 4. This table was compiled from existing literature and from aquifer tests conducted by Board personnel. Data from the aquifer tests were analyzed by using the Theis nonequilibrium formula, as modified by Cooper and Jacob (1946) and Wenzel (1942). The permeability coefficients were computed by dividing the test transmissibility coefficients by the well's effective (utilized) sand thickness. The approximate total coefficient of transmissibility was computed by multiplying the total fresh-water sand thickness by the well's permeability coefficient.

The most permeable sands of the Antlers and Travis Peak Formations occur in the northwest outcrop and adjacent areas of Brown, Callahan, Comanche, Eastland, and Erath Counties. Pumping tests conducted in this area indicate the sands of the Antlers and Travis Peak are characterized by permeability coefficients ranging from approximately 87 to 235 gallons per day per square foot (gpd/ft^2). Because of this range in permeability and the extreme variations in the thickness of the water-saturated sands, coefficient of transmissibility values of 0 to 20,000 gallons per day per foot (gpd/ft) can be expected. Test data in Comanche County show coefficient of storage values ranging from 0.000049 to 0.026. The variation in storage values is to be expected since ground water in the outcrop occurs under both water-table and artesian conditions.

The sands within the calcareous facies of the Travis Peak Formation in west-central Texas (Figure 23) exhibit extremely low permeabilities due to cementation. Pumping tests conducted in the calcareous facies area indicate that coefficients of permeability range from 1 to 20 gpd/ft^2. The low coefficients of permeability and the relatively thin sand thicknesses combine to produce very low coefficients of transmissibility that range from 0 to 1,000 gpd/ft.

In the remainder of the region, excluding the northwest outcrop and calcareous facies areas, ground water within the Hensell and Hosston Members of the Travis Peak Formation is under artesian conditions. Test data in Table 4 indicate that coefficients of permeability of the Hosston range from approximately 17 to 171 gpd/ft^2. In general, permeabilities in the vicinity of the Balcones Fault Zone appear to be low. This could be due to the faults producing a barrier effect on the pump-test data or the faults causing decreases in permeabilities. Excluding these coefficient of permeability values adjacent to the Balcones Fault Zone, the average coefficient of permeability for the Hosston is about 77 gpd/ft^2. The Hosston thickens considerably downdip, therefore coefficient of transmissibility values up to 45,000 gpd/ft can be expected in the downdip areas. The artesian storage coefficients obtained from Table 4 for the Hosston range from 0.000028 to 0.000077.

Test data from Table 4 for the Hensell Member in the downdip region, show coefficients of permeability ranging from 26 to 126 gpd/ft^2. The Hensell thins and becomes shaly downdip, downdip, therefore a range in coefficients of transmissibility from approximately 0 to 15,000 gpd/ft could be expected in the region. Lack of test data prohibits assigning a coefficient of storage range for the Hensell Member, however, storage values should be somewhat less than those of the Hosston Member.

The coefficients of transmissibility and storage may be used to predict future drawdowns of water levels caused by pumping. Figures 7 and 8 show the relation of decline in water levels to the distance from the center of pumping for different coefficients of transmissibility in the Hensell and Hosston Members of the Travis Peak Formation. The graphs are based on a well or group of wells pumping at an indicated rate for 1 year and having certain coefficients of transmissibility and storage. For example, on Figure 8, if the coefficients of transmissibility and storage are 1,000 gpd/ft and 0.00005, respectively, the drawdown or decline in the water level would be about 25 feet at a distance of 1 mile from a well or group of wells discharging 50 gallons per minute (gpm) for 1 year.

Figures 9 and 10 show the relation of decline to time and distance from the center of pumping under artesian conditions for the Hensell and Hosston Members of the Travis Peak Formation. Figure 11 shows the same relationship for the Hosston under water-table conditions. These illustrations indicate that the rate of decline decreases with time and that the decline caused by pumping is proportional to the amount of time a well or well field is pumped. For example, on Figure 10, if the decline 200 feet from a pumping well is 45 feet after 300 gpm has been pumped for 1 year, the decline would be about 61 feet after 300 gpm has been pumped for 100 years. The total decline at any one place within the cone of depression or influence of wells within a well field would be the sum of the influences of all wells within the well field.

Changes in Water Levels

The changes in water levels of observation wells completed in the Antlers and Travis Peak Formations are illustrated by hydrographs and a water-level decline map. Hydrographs of wells (Figure 6) in Callahan, Comanche, and Eastland Counties show water-level fluctuations which are seasonal in nature. The water-level declines correlate with the large irrigation pumpage in the summer months. In the fall and winter, water levels are recovering due to small withdrawals and recharge of the permeable sands by rainfall.

The largest water-level declines in the Hensell and Hosston Members have taken place in the area adjacent to Interstate Highway 35. The long-term water-level declines and seasonal changes in this region are illustrated by Figures 12 and 13, and the amount of decline from 1900 to 1967 is illustrated by Figure 42. This steady decline is due to the low permeability of the water-producing sands and the large amount of ground water which is used for industrial and public supply purposes.

Table 4.—Results of Pumping Tests

Aquifer: Kgr, Glen Rose Formation; Ktp, Travis Peak Formation; Khe, Hensell Member of the Travis Peak Formation; Kpe, Pearsall Member of the Travis Peak Formation; Kho, Hosston Member of the Travis Peak Formation.

Coefficient of transmissibility values shown are the averages from drawdown and recovery test data unless indicated differently by footnotes.

WELL	AQUIFER	COEFFICIENT OF TRANSMISSIBILITY FROM TEST (GPD/FT)	EFFECTIVE SAND THICKNESS (FEET)	COEFFICIENT OF PERMEABILITY (GPD/FT^2)	TOTAL FRESH WATER SAND THICKNESS (FEET)	APPROXIMATE TOTAL COEFFICIENT OF TRANSMISSIBILITY (GPD/FT)	COEFFICENT OF STORAGE	DRAWDOWN OR RECOVERY (FEET)	TIME AFTER WELL TURNED ON OR OFF (HOURS)	AVERAGE YIELD (GPM)	SPECIFIC CAPACITY (GPM/FT)
Bell County											
AX-40-53-505	Kho	8,100 a/	95	85	95	8,100	–	36.4	41.00	120.0	3.3
AX-40-54-501	Ktp	14,100	–	–	–	–	–	33.4	6.00	170.0	5.1
AX-40-59-102	Kgr,Ktp	40 a/	39	1	39	40	–	377.0	4.66	35.0	.1
AX-40-60-801	Khe,Kho	8,700 b/	90	97	90	8,700	0.000043	105.0	24.00	390.0	3.7
AX-40-60-901	Khe,Kho	8,300 b/	99	84	99	8,300	–	91.0	24.00	500.0	5.5
AX-40-60-904	Khe,Kho	9,600 b/	108	89	108	9,600	.000042	103.0	24.00	440.0	4.3
AX-40-60-905	Khe,Kho	8,800 b/	104	85	104	8,800	.000050	153.0	16.00	520.0	3.4
Bosque County											
BB-40-03-603	Kho	7,300	94	78	120	9,300	–	151.0	4.00	346.0	2.3
BB-40-12-803	Khe,Kpe	6,700	53	126	53	6,700	–	100.0	4.00	242.0	2.4
BB-40-21-701	Ktp	7,200	–	–	–	–	–	50.0	4.00	220.0	4.4
Burnet County											
BT-57-15-705	Ktp	1,000 c/	–	–	–	–	–	–	.50	47.0	1.0
BT-57-24-101	Ktp	1,000	51	20	51	1,000	.000042	–	–	–	–
BT-57-24-103	Ktp	800	51	16	51	800	–	50.0	4.00	50.0	1.0
Comanche County											
DY-31-60-215	Kho	6,500 d/	–	–	–	–	–	37.4	72.00	80.0	2.1
DY-31-60-216	Kho	9,900	50	198	56	11,100	.021	–	–	–	–
DY-31-60-217	Kho	10,100	45	224	56	12,600	.026	–	–	–	–
DY-31-60-218	Kho	12,700	54	235	55	12,900	.013	–	–	–	–
DY-31-60-219	Kho	10,700	52	206	56	11,500	.021	–	–	–	–
DY-31-60-220	Kho	12,200	55	222	57	12,600	.015	–	–	–	–
DY-41-14-106	Kho	3,800	25	152	45	6,800	–	81.6	16.00	61.1	.8
DY-41-14-107	Kho	3,900	30	130	45	5,900	.000049	–	–	–	–
Coryell County											
HB-40-26-102	Kho	4,800	52	92	89	8,200	–	41.5	24.00	74.0	1.8
HB-40-43-202	Khe,Kho	8,300 e/	82	101	140	14,200	.000056	94.0	24.00	302.0	3.1
HB-40-43-206	Khe,Kho	9,400 e/	91	103	140	14,500	.000084	101.0	24.00	302.0	3.0
Erath County											
JP-31-55-107	Ktp	6,000	69	87	140	12,200	.00023	–	–	–	–
JP-31-55-202	Ktp	5,100	–	–	–	–	.0011	–	–	–	–
JP-31-55-205	Ktp	–	69	–	140	–	–	–	12.00	148.3	–
JP-31-55-801	Khe,Kho	11,500	124	93	165	15,300	–	47.8	14.00	227.0	4.8
Falls County											
JR-39-33-604	Kho	2,200	63	35	460	16,100	–	198.0	4.00	95.0	.5
Hamilton County											
LA-41-08-301	Ktp	13,000	–	–	–	–	–	26.0	11.00	167.0	6.4
LA-41-24-401	Khe,Kho	1,800	89	20	133	2,700	–	44.0	4.00	103.0	2.3
LA-41-24-403	Khe	3,800	56	68	70	4,800	–	25.0	3.00	95.0	3.8
Hill County											
LW-32-53-902	Khe	5,200	73	71	73	5,200	–	57.0	2.00	134.0	2.4
LW-32-55-904	Kho	1,500	90	17	117	2,000	–	185.0	6.00	171.0	.9

Table 4.—Results of Pumping Tests—Continued

WELL	AQUIFER	COEFFICIENT OF TRANSMISSIBILITY FROM TEST (GPD/FT)	EFFECTIVE SAND THICKNESS (FEET)	COEFFICIENT OF PERMEABILITY (GPD/FT2)	TOTAL FRESH WATER SAND THICKNESS (FEET)	APPROXIMATE TOTAL COEFFICIENT OF TRANSMISSIBILITY (GPD/FT)	COEFFICIENT OF STORAGE	DRAWDOWN OR RECOVERY (FEET)	TIME AFTER WELL TURNED ON OR OFF (HOURS)	AVERAGE YIELD (GPM)	SPECIFIC CAPACITY (GPM/FT)
Hill County—Continued											
LW-39-10-201	Kho	4,000 a/	55	73	215	15,600	—	204.0	4.00	229.0	1.1
LW-40-06-501	Kho	2,800 f/	—	—	—	—	0.000028	—	1.00	297.0	1.8
Johnson County											
PX-32-54-101	Kho	3,200 g/	66	48	80	3,900	—	92.6	3.00	168.0	1.8
McLennan County											
ST-40-16-404	Kho	1,950 a/	107	18	120	2,200	—	138.0	1.17	250.0	1.8
ST-40-16-501	Kho	1,300	50	26	140	3,600	—	119.0	2.00	100.0	.8
ST-40-24-102	Kho	2,500	79	32	115	3,600	—	122.0	4.00	135.0	1.1
ST-40-24-801	Kho,Kpe	2,900 a/	135	21	191	4,100	—	—	1.37	560.0	—
ST-40-24-802	Kho,Kpe	2,700 a/	111	24	191	4,600	—	—	1.38	513.5	—
(Feb. 11, 1953) ST-40-24-803	Kho	3,100	165	19	165	3,100	—	447.0	94.00	650.0	1.5
(Mar. 31, 1964) ST-40-24-803	Kho	3,300	165	20	165	3,300	—	314.0	8.00	768.0	2.4
ST-40-31-701	Kho	5,500	62	89	124	11,000	.000066	—	—	—	—
ST-40-32-403	Kho	4,500 h/	140	32	195	6,300	—	—	48.00	—	2.1
ST-40-37-501	Khe	1,100	43	26	43	1,100	—	201.0	5.00	155.0	.8
ST-40-39-106	Kho	5,700	72	79	125	9,900	—	248.0	6.00	580.0	2.3
ST-40-39-702	Kho	9,100	91	100	152	15,200	—	71.0	2.66	191.0	2.7
ST-40-46-403	Kho	8,200	115	71	115	8,200	.000028	—	—	—	—
ST-40-46-801	Kho	5,600 a/	59	95	89	8,400	—	43.0	66.00	100.0	2.3
Somervell County											
XJ-32-50-303	Kho	13,500 d/	—	—	—	—	—	133.0	16.00	614.0	4.6
Travis County											
YD-58-43-702	Ktp	700	15	47	225	10,500	—	22.6	40.37	12.8	.6
YD-58-43-703	Kho	600	—	—	—	—	—	53.2	8.03	19.6	.4
YD-58-43-801	Ktp	1,400		—	—	—	—	50.5	1.68	40.0	.8
YD-58-44-201	Kho	1,900 a/	60	32	310	9,800	—	50.9	1.10	48.8	1.0
Williamson County											
ZK-58-10-201	Khe	1,800	32	56	32	1,800	—	47.5	4.00	60.0	1.3
ZK-58-10-202	Khe	1,800	32	56	32	1,800	.000023	—	—	—	—
ZK-58-18-401	Ktp	5,400	60	90	80	7,200	—	9.8	3.00	25.1	2.6
ZK-58-21-202	Kho	34,800	203	171	248	42,500	—	56.3	4.00	310.0	5.5
ZK-58-21-203	Kho	25,200	203	124	248	30,800	.000077	—	—	—	—
ZK-58-29-604	Kho	28,500	423	67	527	35,500	—	163.9	4.00	1,089.0	6.6

a/ Aquifer coefficients computed from recovery test.
b/ Aquifer coefficients obtained by averaging certain transmissibility and storage values, W. F. Guyton and W. O. George, 1943.
c/ J. R. Mount, 1962.
d/ Aquifer coefficients computed from drawdown test.
e/ Aquifer coefficients obtained by averaging certain transmissibility and storage values, N. A. Rose, 1943.
f/ J. R. Mount, 1963.
g/ Aquifer coefficients obtained by personal communication from G. L. Thompson, U.S. Geological Survey, January 1968.
h/ W. O. George and B. A. Barnes, 1945.

Chemical Quality

Because of the large areal extent of the Travis Peak Formation and the lateral variations in lithology, porosity, permeability, and transmissibility, the discussion of chemical quality is with respect to three areas: (1) the northwest area, where the Antlers and Travis Peak Formations crop out and areas immediately adjacent to the outcrop in Brown, Callahan, Comanche, Eastland, and Erath Counties; (2) the area within the calcareous facies of the Travis Peak Formation in Bell, Brown, Burnet, Coryell, Hamilton, Lampasas, Mills, and Williamson Counties; and (3) the remainder of the study region not included in the northwest outcrop or the calcareous facies area. Only wells completed in the Hensell or Hosston Members of the Travis Peak Formation are considered in this remaining area.

Data on the chemical quality of water in the Antlers and Travis Peak Formations throughout the study region are shown on Figures 35, 36, and 37. Ranges of constituents and properties of water from representative wells in the northwest outcrop and adjacent areas are given in Table 5. The ranges also appear within parentheses throughout the following discussion of chemical quality.

The water in and near the northwest outcrop area is a hard (98-550 mg/l $CaCO_3$), sodium bicarbonate type, generally of good quality, with a range in temperature from about (59°F) (15°C) to (75°F) (24°C).

Ground water in Comanche, Eastland, Erath, and adjacent counties is used primarily for irrigation and is generally considered satisfactory for the crops grown. Its salinity hazard is medium to high, while its sodium (alkali) hazard is generally low as shown on Figure 14. Wilcox (1955) concludes that the classification of the U.S. Salinity Laboratory Staff, shown on Figure 14, is not directly applicable to supplemental waters used in areas of relatively high rainfall. Therefore, because of the high annual rainfall and crop rotation practice in the study region, the U.S. Salinity Laboratory Staff system may not be applicable. Other constituents generally considered in evaluating the chemical quality of irrigation waters are percent sodium (4-64) and boron (0.06-0.4 mg/l), which according to Scofield (1936) would rate good for use on sensitive crops, and excellent for use on semitolerant and tolerant crops.

Most domestic and public ground-water supplies in the

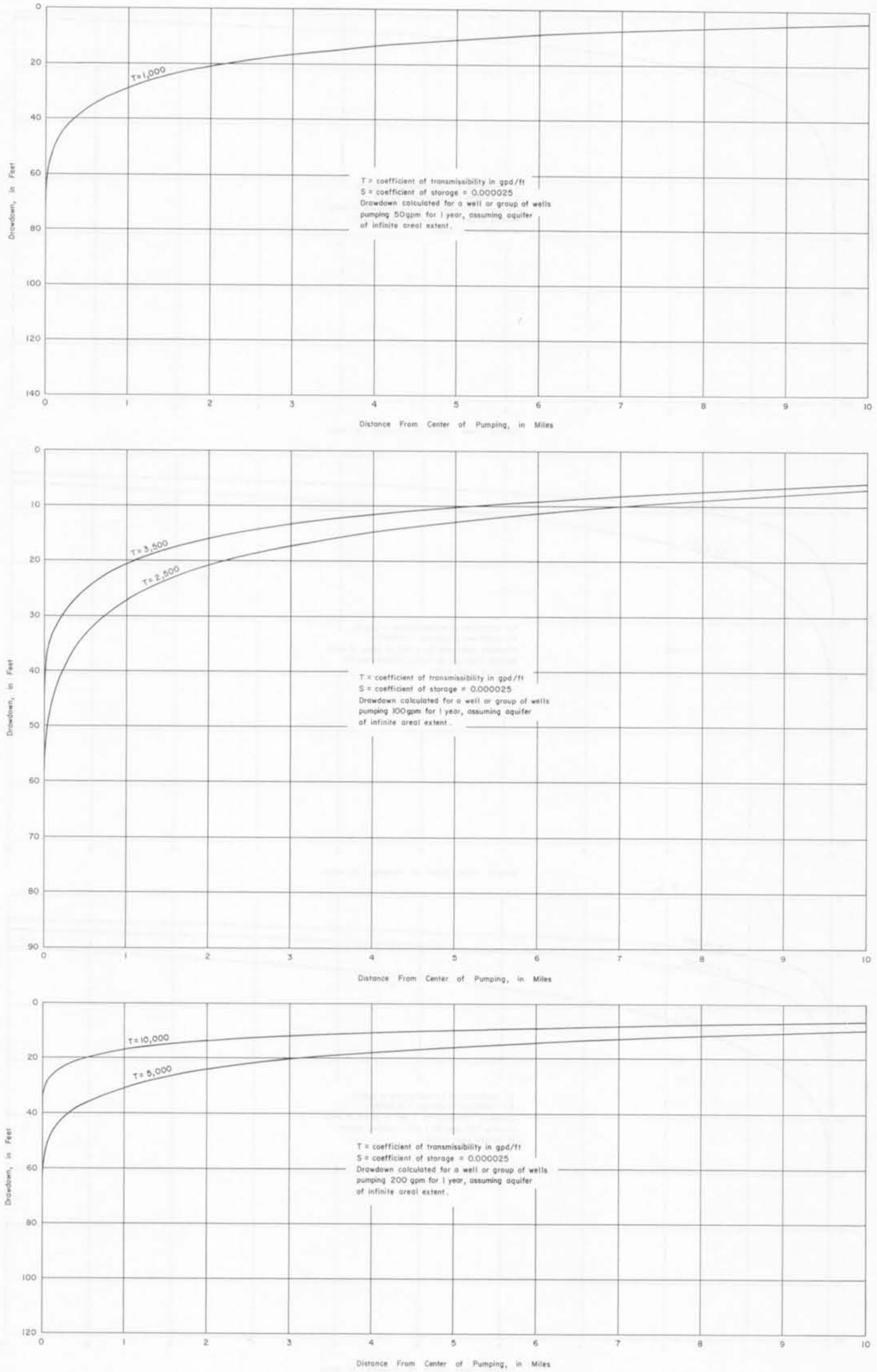

Figure 7

Relation of Decline in Water Levels to Transmissibility and Distance for Artesian Conditions in the Hensell Member of the Travis Peak Formation

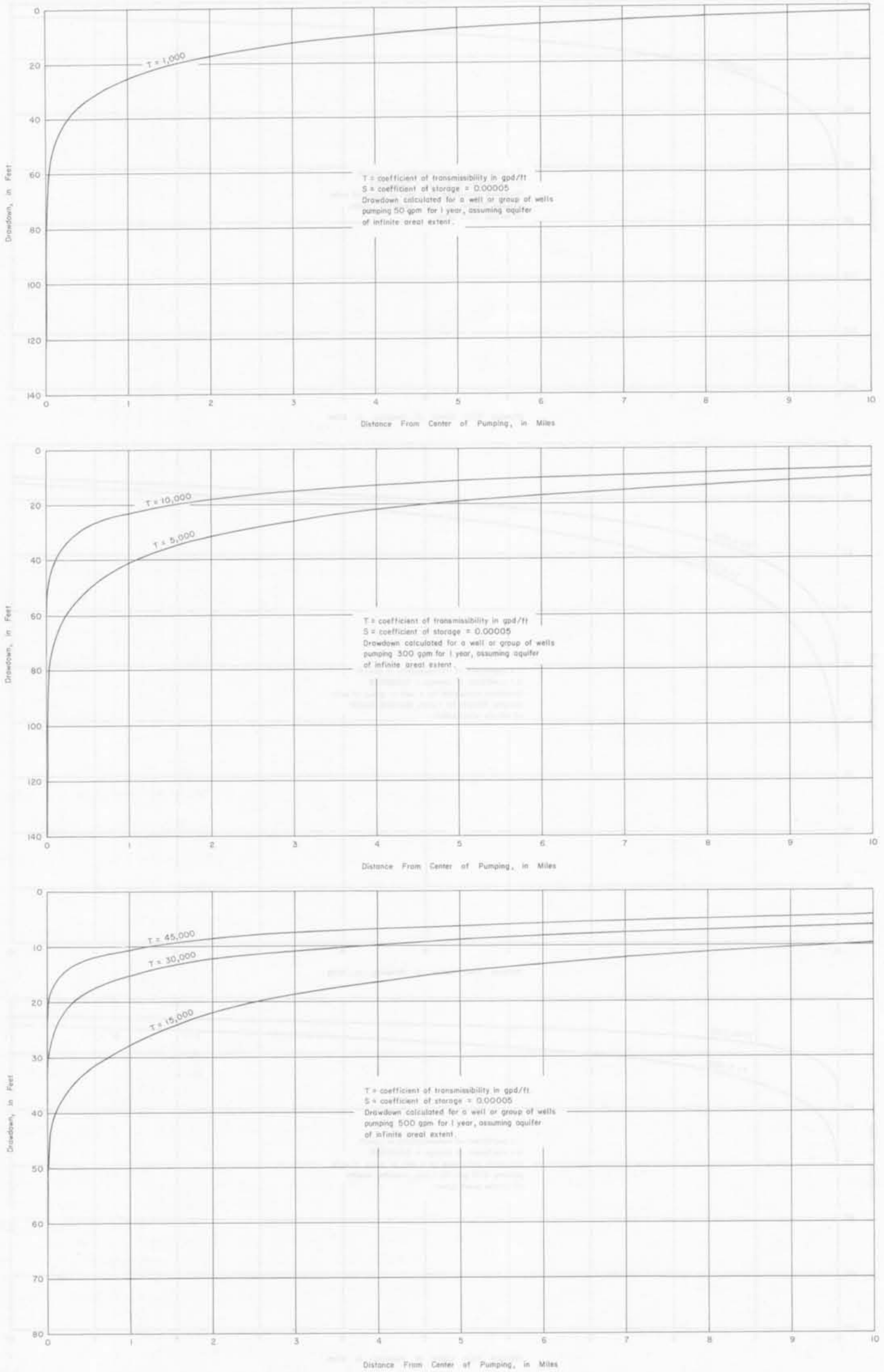

Figure 8

Relation of Decline in Water Levels to Transmissibility and Distance for Artesian Conditions in the Hosston Member of the Travis Peak Formation

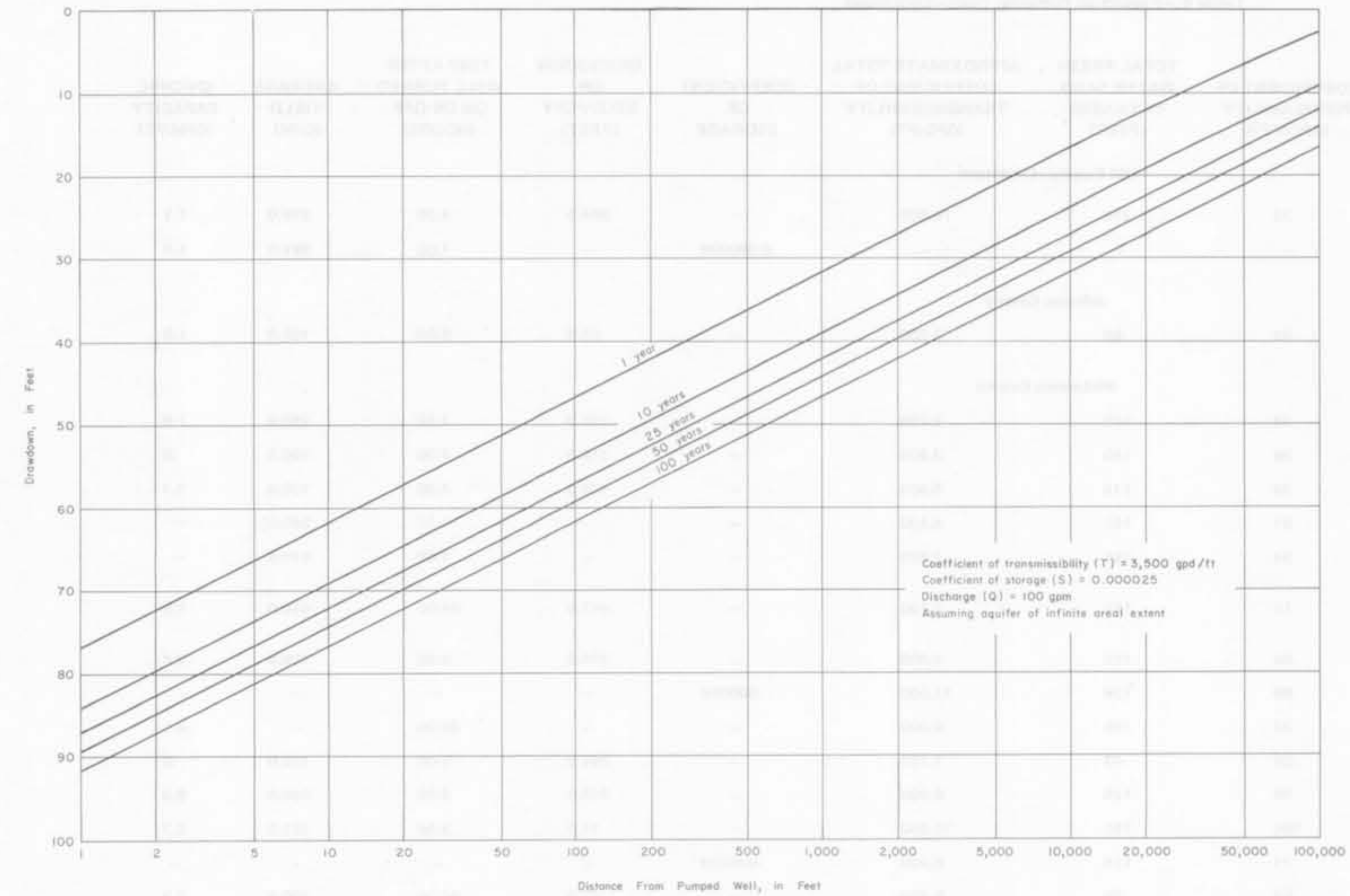

Figure 9

Relation of Decline in Water Levels to Time and Distance as a Result of Pumping Under Artesian Conditions From the Hensell Member of the Travis Peak Formation

Table 5.—Range of Constituents and Properties of Ground Water From Representative Wells in the Antlers and Travis Peak Formations in the Northwest Outcrop and Adjacent Areas

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

CONSTITUENT OR PROPERTY	CALLAHAN COUNTY	EASTLAND COUNTY	ERATH COUNTY	COMANCHE COUNTY	BROWN COUNTY
Silica (SiO_2)	19 - 40	10 - 29	11 - 18	13 - 33	13 - 17
Iron (Fe)	.03- .21	.4 - .8	.1- 1.4	.02- .3	—
Calcium (Ca)	95 - 142	30 - 174	46 - 132	40 - 144	58 - 100
Magnesium (Mg)	13 - 31	2 - 46	8 - 37	4 - 62	52 - 82
Sodium and Potassium (Na + K)	6 - 198	3 - 115	9 - 93	4 - 79	41 - 330
Bicarbonate (HCO_3)	265 - 455	134 - 468	209 - 472	128 - 461	397 - 434
Sulfate (SO_4)	39 - 99	10 - 71	9 - 105	11 - 118	52 - 130
Chloride (Cl)	36 - 217	3 - 213	14 - 143	6 - 188	44 - 81
Fluoride (F)	.4 - 1.3	0 - 2.4	.2- .6	.3 - 1.1	.5- 1
Nitrate (NO_3)	.4 - 70	0 - 35	.4- 27	.4 - 31	.4- 9
Boron (B)	—	.08- .4	.1- .2	.06- .2	—
Dissolved solids	409 - 980	182 - 731	271 - 579	219 - 770	500 - 791
Total hardness ($CaCO_3$)	296 - 433	98 - 476	196 - 419	117 - 550	379 - 484
Percent sodium (percent Na)	21 - 53	4 - 45	6 - 44	4 - 36	16 - 64
Specific conductance (micromhos at 25°C)	675 -1,550	300 -1,270	458 -1,050	349 -1,290	862 -1,035
pH	7.0 - 7.4	6.8 - 7.5	7.2- 7.7	6.7 - 7.9	7.3- 7.9
Sodium adsorption ratio (SAR)	.9 - 4.4	.1 - 2.5	.2 - 2.5	.8 - 1.8	.8- 7.1

northwest outcrop and adjacent area are obtained from the Travis Peak Formation, although the concentrations of dissolved solids (1820980 mg/l), iron (0.02-1.4 mg/l), and fluoride (0-2.4 mg/l) in in some cases exceed the standards set by the U.S. Public Health Service. Chloride (3-217 mg/l) and sulfate (9-130 mg/l) are well within the prescribed limits. Treatment other than chlorination for public supply does not seem necessary except possibly in areas with high iron concentrations.

Ground water in the northwest outcrop and adjacent area is generally not suitable for industrial use due to its high content of silica (10-40 mg/l), iron, hardness, and sodium bicarbonate. Testing and effective treatment should be considered by future potential industry in the area.

Contamination reported to have occurred locally from improper disposal of oil-field brines is illustrated on Figure 35. Proper disposal and plugging methods will help correct this situation with time.

Ranges of constituents and properties of water from representative wells in and adjacent to the calcareous facies of the Travis Peak Formation are given in Table 6. The water usually is a hard (98-546 mg/l $CaCO_3$), sodium bicarbonate type of poor quality, and ranges in temperature from (70°F) (21°C) to (84°F) (29°C).

Ground water in this area is primarily used for domestic and public supply, although generally the ranges of major constituents exceed U.S. Public Health Service standards. This water has been and continues to be used, due to the unavailability of a more suitable supply, without any apparent ill effects on the users. Some of the constituent ranges in mg/l are: chloride (15-530), fluoride (0.1-4.4),iron (0.03-2), nitrate (0-168), sulfate (11-700), and dissolved solids (372-2,280). Treatment, other than chlorination for public supply, is generally not practiced. practiced.

Irrigation is uncommon in this area primarily because of the thin calcareous soil cover and rough topography which supports very little farming. The ground water in this area has a very high sodium (alkali) hazard and salinity hazard based on its SAR (0.2-35.4) and specific conductance (643-3,760). In addition, it has a high percent sodium (5-95) and high dissolved-solids content, all of which make it undesirable for irrigation.

Industrial use of ground water in this area is negligible since the water is generally unsuitable because of its high iron, hardness, and sodium bicarbonate contents. Consideration should be given to testing and effective treatment by future potential industrial users.

Contamination of ground water in this area occurs generally when saline water from the Glen Rose Formation is allowed to enter and mix with native Travis Peak water. This occurs as a result of poorly constructed wells which have little or no casing, wells which have been completed (perforated) opposite undesirable water zones, and wells with corroded casings. Another factor which contributes to the poor quality of ground water found in the area is the low permeability of the aquifer. This reduced permeability is due to calcareous cementation which restricts the recharge and flushing so vital in maintaining good quality in ground water.

Water from the Hensell Member of the Travis Peak Formation in the downdip areas, but not within the calcareous facies, is of a sodium bicarbonate type. The chemical quality of the water, although generally good, exhibits a gradual deterioration with distance from the northwest outcrop area and toward the south-southeast, as illustrated on Figure 36. Connate water present during deposition is replaced to a lesser degree downdip, consequently the quality of the ground water decreases. This decline in quality results from the aquifer's loss of permeability which in turn restricts the influx of fresh waters. Loss of permeability in Travis County and western Williamson County is due to calcareous cementation of the aquifer, while in the east and southeast it is a product of the change in depositional facies from sand to shale. Ranges of constituents and

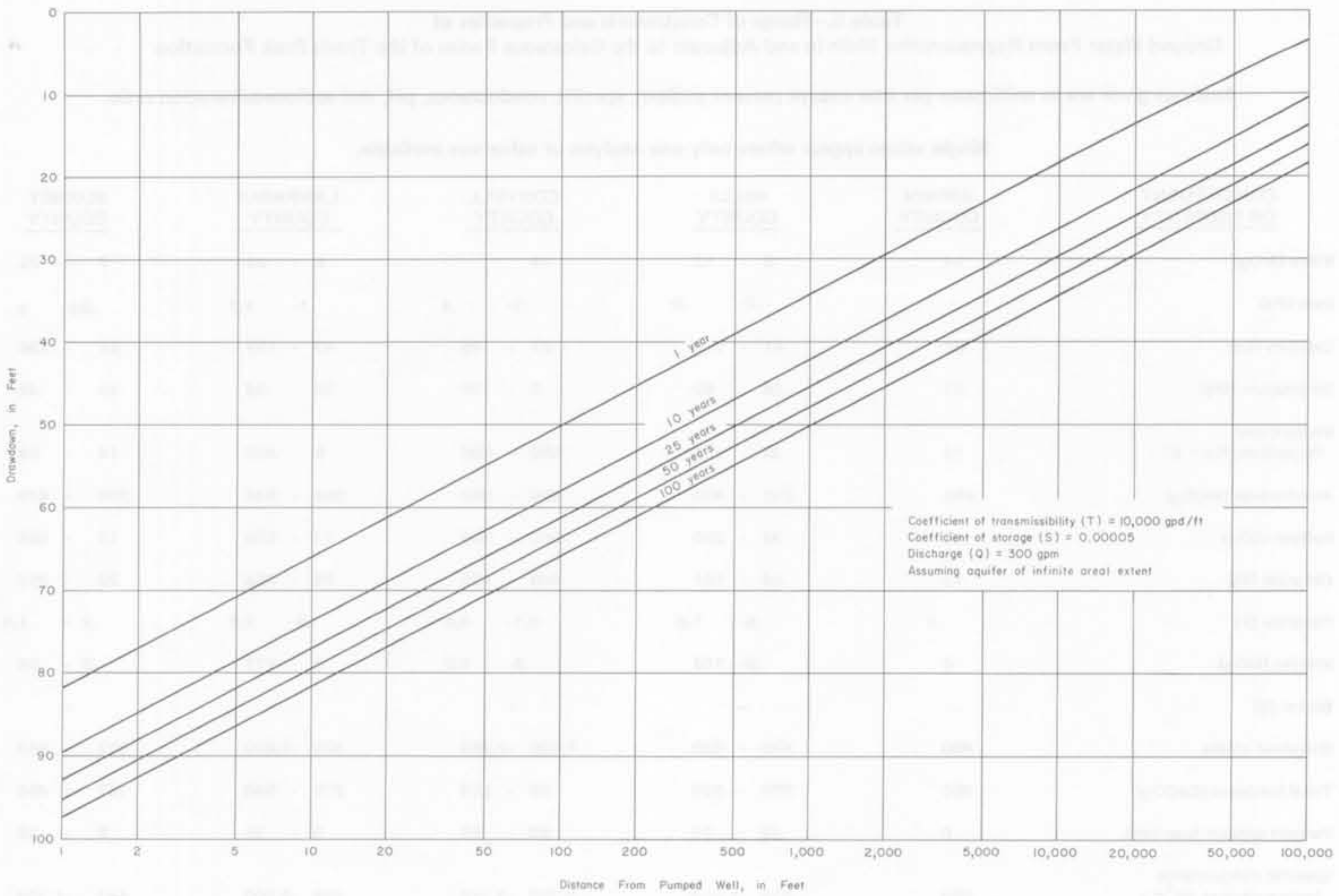

Figure 10

Relation of Decline in Water Levels to Time and Distance as a Result of Pumping Under Artesian Conditions From the Hosston Member of the Travis Peak Formation

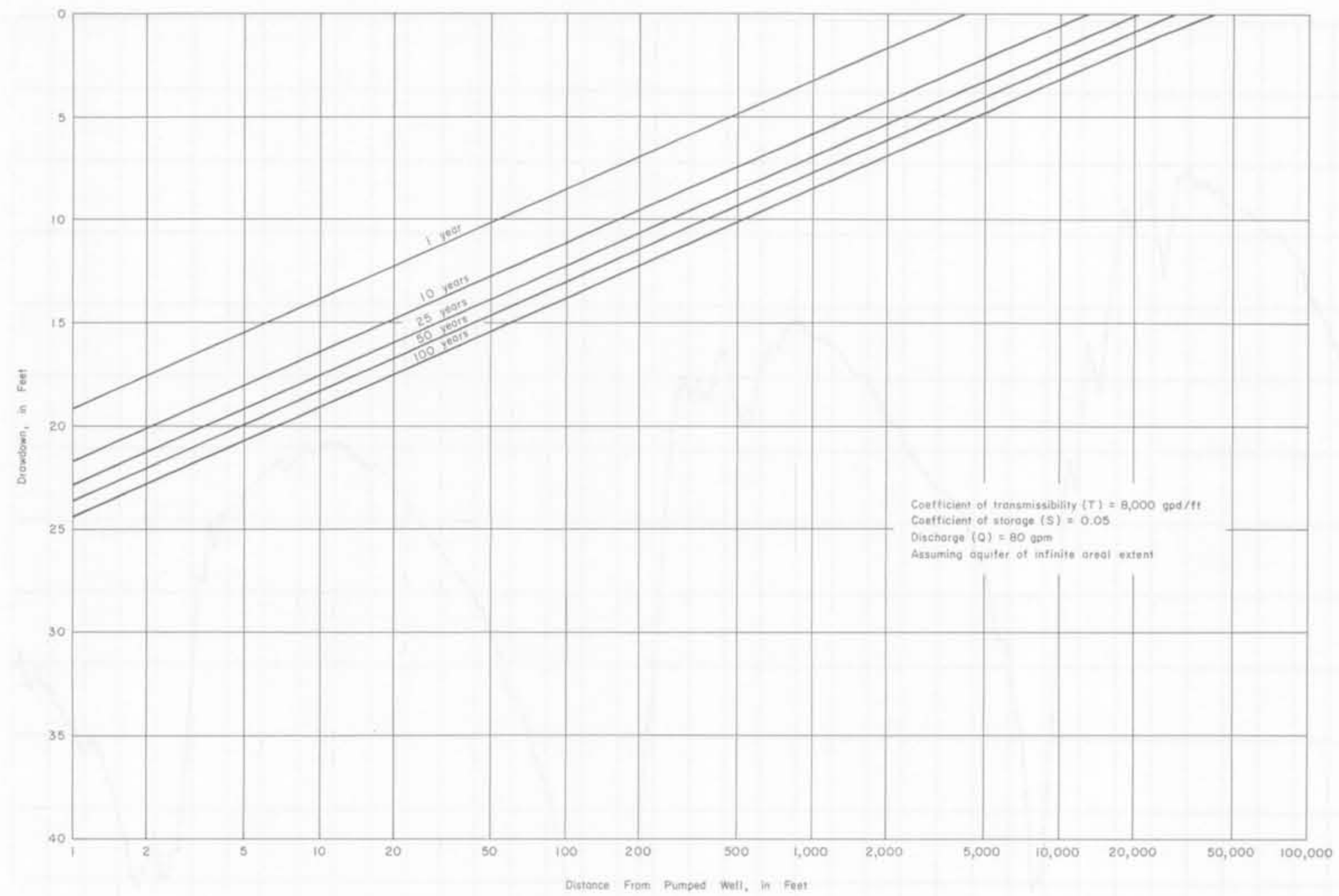

Figure 11

Relation of Decline in Water Levels to Time and Distance as a Result of Pumping Under Water-Table Conditions From the Hosston Member of the Travis Peak Formation

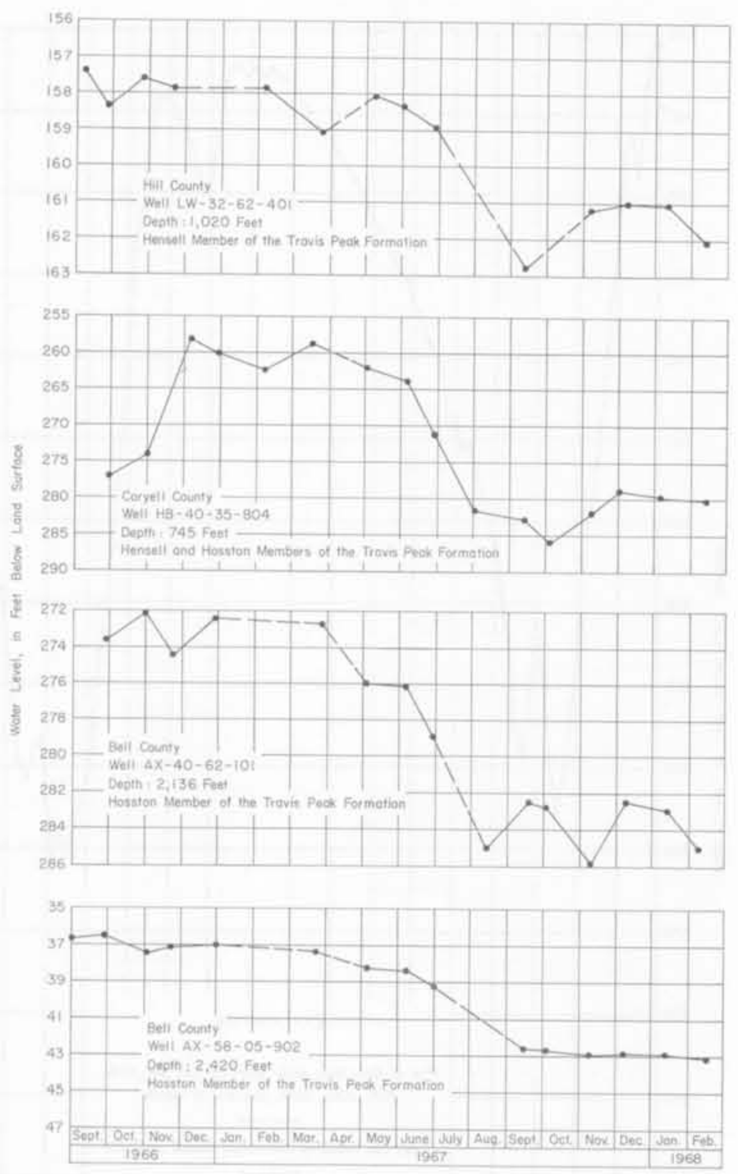

Figure 12

Hydrographs of Water Levels in Wells Completed in the Travis Peak Formation Under Artesian Conditions

properties of the water from representative wells in the Hensell Member of the Travis Peak Formation are shown in Table 7.

Water from the Hensell, in this area, is primarily used for domestic and public supply, although its iron (0.02-2.2 mg/l), fluoride (0.1-6 mg/l), and dissolved solids (311-1,470 mg/l) may generally exceed the U.S. Public Health Service standards. Other constituents or properties such as nitrate (0-64 mg/l), chloride (11-334 mg/l), sulfate (24-510 mg/l), hardness (3-398 mg/l $CaCO_3$) are generally low over most of the area except adjacent to the calcareous facies where chloride, sulfate, and hardness exceed the U.S. Public Health Service standards. Treatment other than chlorination for public supply is generally not exercised.

Hensell water, in this area, is generally not suitable for irrigation because of its high sodium hazard (SAR 0.3-32), high salinity hazard (specific conductance 554-2,464), and high percent sodium (7-98). An appraisal of boron was not made because of the lack of data.

Water from the Hensell is generally favorable for industrial use in most of the area except where hardness, iron, and dissolved solids are high. Silica (3-17 mg/l) and temperatures of (66°F) (19°C) to (84°F) (29°C) are relatively low, making it highly desirable for use in boilers and cooling processes.

Contamination, resulting in a deterioration of water quality, is restricted to local areas and generally occurs when undesirable saline water enters along fault planes or intermingles with the more desirable water in poorly constructed and completed wells.

Water from the Hosston Member of the Travis Peak Formation in the downdip areas, but not within the calcareous facies, is a sodium bicarbonate type, generally of better quality than the Hensell. Its chemical quality, like that of the Hensell, decreases gradually downdip from the outcrop as illustrated on Figure 37. This general decrease in chemical quality can be attributed to a reduced replacement of connate water by fresh water progressively downdip from the outcrop. In the extreme southeast, faulting has reduced the movement and flushing of connate water and may have allowed undesirable saline water to enter along fault planes. East of the Balcones Fault Zone, water in the lower part of the Hosston is of better quality because of the coarse and permeable nature of the sands, while the saline water found in the upper part may have resulted from the finer, less permeable sand impeding the flushing action. Ranges of constituents and properties of water from representative wells in the Hosston Member of the Travis Peak Formation are presented in Table 8.

The water within the Hosston downdip and immediately adjacent to the calcareous facies of the Travis Peak Formation in western Bell and Williamson Counties is of poor quality. This is due to the low permeability within the calcareous facies, which impedes the movement and flushing action of ground water within and adjacent to the facies boundary.

Water from the Hosston in this area is primarily used for domestic and public supply, even though the iron (0-3.6 mg/l), fluoride (0-5.3 mg/l), and dissolved solids (362-1,885 mg/l) content may generally exceed the U.S. Public Health Service standards. Nitrate (0-20 mg/l), chloride (16-528 mg/l), sulfate (20-900 mg/l), and hardness (5-500 mg/l $CaCO_3$) are usually low; however, chloride increases adjacent to the calcareous facies, sulfate increases east of the Balcones Fault Zone, and hardness increases in both areas. All increases exceed the U.S. Public Health Service standards. Chlorination, in public supplies, is generally the only treatment exercised except at Bartlett, which treats for fluoride, and Little River, Taylor, and Buckholts, which aerate to remove the hydrogen sulfide gas.

Irrigation is not an important use of Hosston water because dryland farming is generally practiced in this area, and because the quality of water is not suitable due to a high sodium hazard (SAR 0.2-50), salinity hazard (specific conductance 632-3,840), and percent sodium (5-99).

The industrial application of Hosston water includes its use in processing, cooling, and boilers. Silica is generally low making its use in boilers desirable. Some restriction or treatment may be necessary in areas where iron, hardness, temperature, and dissolved-solids content are excessive.

Contamination is restricted to the local variations in quality resulting from improperly constructed or completed wells and faulting which allows undesirable saline waters to enter and deteriorate the native ground water. In the extreme southeast, major faulting (Mexia-Talco Fault Zone) has caused pronounced displacement and may contribute to water quality decline by restricting water movement and flushing or by permitting undesirable saline water to enter along fault planes.

Utilization and Development

Prior to 1880 there was no development of ground water from the Antlers and Travis Peak Formations other than small amounts used for domestic, livestock, and public supply purposes. Later Hill (1901) and Adkins (1923) reported many wells completed in the Travis Peak Formation, which supplied towns and a few enterprising farmers. Since the early 1900's, the Travis Peak has been developed to provide large amounts of ground water for domestic, livestock, public supply, industrial, and irrigation needs. At present, residents in Comanche and Eastland Counties are rapidly developing the Antlers and Travis Peak Formations for irrigation purposes.

In 1967, about 48,600 acre-feet of ground water was pumped from the principal Cretaceous aquifers in the region. Approximately 87 percent of this ground water was supplied from the Antlers and Travis Peak Formations. The estimated amounts and uses of ground water pumped in 1967, by aquifer, are shown in Table 9.

Public Supply

The increase in population and modernization of homes in towns and cities have created a steady, increasing demand for ground water over the years. This demand is illustrated by Figure 15, which shows the amount of ground water used for public supply purposes from 1955 to 1967. In 1967, approximately 16,800 acre-feet of ground water was pumped from the Antlers and Travis Peak Formations for public supply use. This was about 40 percent of the total amount of ground water used from the Antlers and Travis Peak Formations in the region.

The city of Waco and its suburbs are the largest users of water for public supply in the study region. In 1872, the city had its first water system which obtained its supply from an artesian well that tapped the Travis Peak Formation. Presently the city and its suburbs obtain water from Waco Lake and 33 wells which range in depth from about 1,500 to 2,500 feet. All of the wells are completed in the Travis Peak Formation with most of the wells supplying water from the Hosston Member. In 1967, these wells supplied approximately 3,000 acre-feet of water for the city and surrounding areas. This is 18 percent of the total amount of ground water used for public supply from the Antlers and Travis Peak Formations.

The city of Stephenville is the second largest user of ground water from the Travis Peak Formation for public supply. In 1967, the city pumped about 1,460 acre-feet of ground water, which is approximately 9 percent of the total amount of ground water used for public supply from the Antlers and Travis Peak Formations. Stephenville obtains its supply from approximately 19 wells located within the city limits and southeast of town. These wells are completed in the entire sand section of the Travis Peak (Hensell and Hosston) and range in depth from 400 to 511 feet.

The city of Belton is the third largest user of ground water from the Travis Peak Formation for public supply. In 1967, the city used approximately 1,140 acre-feet of ground water, which is about 7 percent of the total amount of water used for public supply from the Antlers and Travis Peak Formations. The water is pumped from four wells which range in depth from 1,190 to 1,293 feet. It is believed these wells are completed in the Hosston Member.

The city of Taylor is the fourth largest user of ground water from the Travis Peak Formation for public supply. During 1967, Taylor pumped about 1,120 acre-feet of ground water from the Hosston Member. This is approximately 7 percent of the total amount of water used for public supply from the Antlers and Travis Peak Formations. Taylor obtains its water from three wells ranging in depth from 3,308 to 3,365 feet.

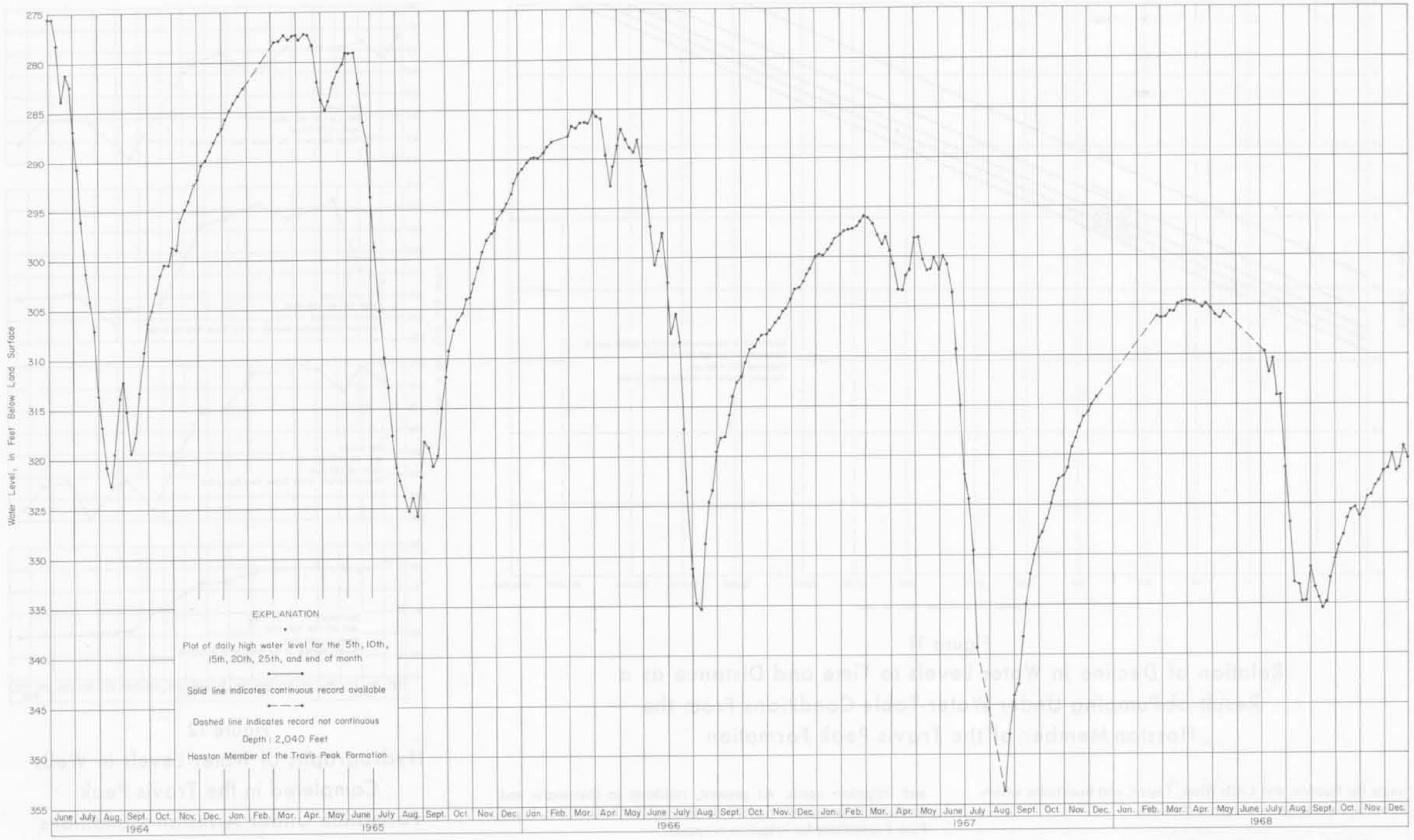

Figure 13

Hydrograph of Water Levels in Recorder Well ST-40-31-802, McLennan County

The city of Hillsboro is fifth largest user of ground water from the Travis Peak Formation for public supply. Hillsboro used about 915 acre-feet of ground water from the Woodbine, Paluxy, and Travis Peak Formations. However, about 90 percent of this ground water was obtained from the Travis Peak Formation. This is approximately 5 percent of the total amount of water used for public supply from the Antlers and Travis Peak Formations. Hillsboro has nine wells ranging in depth from approximately 200 to 2,000 feet. Four wells are completed in the Woodbine, Paluxy, and Travis Peak Formations, two in the Travis Peak only, two in the Paluxy, and one in the Woodbine.

Other towns in the region which used large quantities of ground water from the Travis Peak Formation in 1967 were Gatesville, about 721 acre-feet; Dublin, about 662 acre-feet; DeLeon, about 583 acre-feet; McGregor, about 447 acre-feet from the Hensell Member; Mart, about 381 acre-feet from the Hosston Member; Clifton, about 331 acre-feet; West, about 330 acre-feet from the Hosston Member; Meridian, about 257 acre-feet from the Hosston Member; and Granger, about 215 acre-feet from the Hosston Member.

Industrial

In 1967, as shown in Table 9, approximately 3,700 acre-feet of ground water was pumped from the Antlers and Travis Peak Formations for industrial purposes. This is about 9 percent of the total amount of ground water used from the Antlers and Travis Peak Formations in the study region. Industrial pumpage has remained fairly constant with only minor fluctuations occurring from 1955 to 1967, as illustrated on Figure 16.

Irrigation

In 1967, approximately 1,600 irrigation wells pumped 16,100 acre-feet of ground water for irrigation purposes from the Antlers and Travis Peak Formations. The irrigation pumpage represents 38 percent of the total ground water pumped from the Antlers and Travis Peak Formations during 1967 in the study region. This pumpage was principally from Comanche, Eastland, and Erath Counties. Irrigation ground-water pumpage in these and adjacent counties for the period 1954-67 is illustrated on Figure 17.

The quantity of ground water used for irrigation was estimated from power and yield tests conducted in Comanche, Eastland, and Erath Counties. The following procedure was used to estimate this pumpage: (1) the annual number of kilowatt-hours supplied to the irrigated farms from 1954 through 1967 was obtained from power companies and electrical cooperatives; (2) power and yield tests were conducted on various irrigation wells to determine the average number of gallons produced per kilowatt-hour; (3) the average number of gallons produced per kilowatt-hour was multiplied by the total kilowatt-hours supplied by power companies and electrical cooperatives to determine the approximate annual irrigation pumpage (1954 through 1967) for the outcrop and adjacent areas. The results and data collected from the power and yield tests are given in Table 10. The test locations and approximate locations of irrigation wells in Comanche, Eastland, Erath, and adjacent counties are shown on Figure 38.

Table 6.—Range of Constituents and Properties of Ground Water From Representative Wells in and Adjacent to the Calcareous Facies of the Travis Peak Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

CONSTITUENT OR PROPERTY	BROWN COUNTY	MILLS COUNTY	CORYELL COUNTY	LAMPASAS COUNTY	BURNET COUNTY
Silica (SiO_2)	14	9 - 13	14	5 - 22	7 - 26
Iron (Fe)	—	.2- .6	.1- .4	.1- 1.7	.03- 2
Calcium (Ca)	62	41 - 110	27 - 46	43 - 127	52 - 136
Magnesium (Mg)	57	26 - 62	8 - 37	29 - 96	28 - 49
Sodium and Potassium (Na + K)	11	32 - 227	580 - 806	9 - 408	14 - 69
Bicarbonate (HCO_3)	455	312 - 433	380 - 389	353 - 534	280 - 439
Sulfate (SO_4)	11	32 - 250	560 - 700	13 - 530	16 - 194
Chloride (Cl)	15	44 - 101	468 - 530	22 - 304	20 - 395
Fluoride (F)	.1	.6- 1.8	3.1- 4.4	.4- 2.7	.2 - 1.1
Nitrate (NO_3)	6	.9- 168	.5- 1.8	0 - 111	.8 - 84
Boron (B)	—	—	—	—	—
Dissolved solids	400	476 - 830	1,900 -2,280	422 -1,420	372 - 968
Total hardness ($CaCO_3$)	388	209 - 530	98 - 266	225 - 546	257 - 456
Percent sodium (percent)	6	12 - 70	83 - 95	5 - 78	8 - 25
Specific conductance (micromhos at 25°C.)	680	815 -1,450	2,750 -3,760	655 -2,000	643 -1,300
pH	7.6	7.0- 8.0	7.8	7.1- 8.0	7.2 - 8.1
Sodium-adsorption ratio (SAR)	.2	.6- 6.8	15.5- 35.4	.2- 11.2	.3 - 1.4

The history of irrigation in Comanche, Eastland, Erath, and adjacent counties is illustrated graphically by Figure 17. In the early 1950's, irrigation began to develop at a slow uniform rate largely as a result of the drought years. By the end of 1963, about 180 irrigation wells were supplied from the Antlers and Travis Peak Formations. In 1964 and 1965, irrigation in the area began to accelerate due to the development of an efficient submersible pump and government price supports for peanuts. By the end of 1967, about 1,600 irrigation wells were in operation and capable of producing 80 million gallons per day of ground water. These wells are pumped about 60-70 days annually and the water is generally used to irrigate peanuts and bermuda grass.

Domestic and Livestock

The amount of ground water pumped from the Antlers and Travis Peak Formations for rural domestic and livestock purposes in 1967 was approximately 5,900 acre-feet, as illustrated in Table 9. This represents about 14 percent of the total amount of ground water used from the Antlers and Travis Peak Formations. The amount of ground water pumped in the region for domestic and livestock purposes was estimated by (1) multiplying the average amount of water a person uses by the rural population as listed in the Texas Almanac (1967); (2) multiplying the average amount of water each type of livestock animal uses by the population of each animal type as listed in the almanac; and (3) adding the results.

Rural domestic and livestock pumpage has probably been fairly constant from 1955 to 1967 with minor fluctuations occurring during wet and dry years. The per capita use of water on farms and ranches has probably increased due to the modernization of many rural homes, and the overall rural population has decreased; therefore, the total amount of ground water used has likely remained about the same.

The Digital Computer Model of the Travis Peak Formation

The supply of ground water in the Travis Peak Formation is large, however, the amount of water being withdrawn in the study region exceeds the natural recharge. This ground-water supply is being depleted in the downdip areas by removal of water from storage in the aquifers. One of the primary objectives of this study was the simulation of the Hensell and Hosston Members of the Travis Peak Formation through the use of a digital computer. The simulation process allows the prediction of water-level declines in the aquifers as a result of estimated projected pumpage. Predicted water-level declines provide a means for evaluating the ability of the aquifers to meet anticipated ground-water requirements.

A contract for a digital computer model of the Hensell and Hosston Members was entered into between the consultant firm Dames and Moore of California and the Texas Water Development Board on July 30, 1968. This contract required Dames and Moore to build the aquifer model and furnish the Board with the data that resulted from the study.

The digital computer deals in digits and provides exact numerical answers. The advanced high-speed electronic digital computer is flexible and is able to compute with tremendous speed.

The operation of a digital computer can be compared to a desk calculator. First, a decision must be made in how numbers are to be used in a mathematical process (addition, subtraction, multiplication, or division) and in what sequence. The computations are then performed with the desk calculator and the answers recorded. With the digital computer, the sequence of mathematical operations and the form in which answers are to be presented must still be decided in advance. These decisions are given to the digital computer in the form of instructions, called a

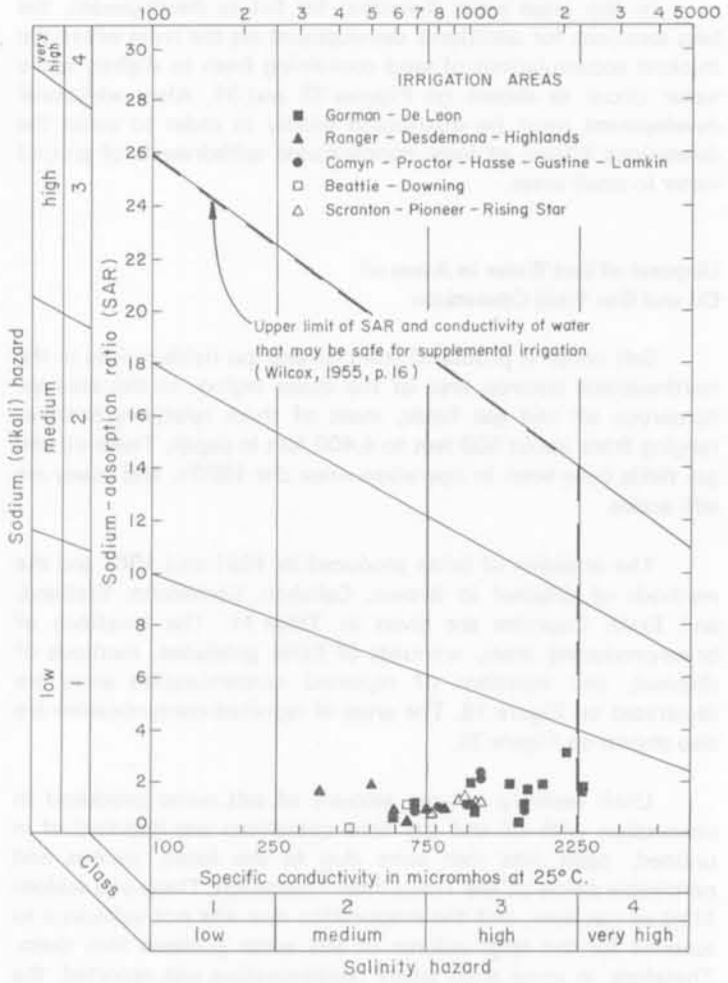

Figure 14

Diagram for the Classification of Irrigation Waters, Showing Quality of Water From Representative Wells in Comanche, Eastland, and Erath Counties (After United States Salinity Laboratory Staff, 1954, p. 80)

program. The program and data are generally given to the computer on punched cards or magnetic tape. The program is then read, memorized, and executed by the computer. Therefore, the operations by which a computer solves a problem are to read and store a program or set of instructions, read and process data according to the program, and present the results.

Procedure

The study region was segmented into 292 subareas called polygons, each containing the Hensell and Hosston aquifers. The center of each polygon for a particular aquifer is called a node. The study area contained 292 node locations; each location has two numbers, one for the Hensell and one of the Hosston, thereby making 584 numbered nodes which were placed on base maps. The node locations for the Hensell and Hosston aquifers in the study region are illustrated on Figures 45 and 48. The Hensell and Hosston nodes are joined in each polygon by a vertical leakage value which represents the Pearsall or the Hammett and Cow Creek Members in the computer simulation. This vertical leakage value enables the computer to analyze the Hensell and Hosston aquifers as a unit.

Coefficients of transmissibility and storage properties of the Hensell and Hosston aquifers were obtained from pumping test data, as presented in Table 4, and aquifer fresh water sand thicknesses were obtained from Figures 33 and 34. These values were assigned to the respective nodes within each polygon. Transmissibility values were reduced in the Balcones Fault Zone in order to compensate for the flow barrier effect caused by the

Table 7.—Range of Constituents and Properties of Ground Water From Representative Wells in the Hensell Member of the Travis Peak Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

CONSTITUENT OR PROPERTY	SOMERVELL COUNTY	HAMILTON COUNTY	BOSQUE COUNTY	HILL COUNTY	CORYELL COUNTY	McLENNAN COUNTY	BELL COUNTY	WILLIAMSON COUNTY	TRAVIS COUNTY
Silica (SiO_2)	11 - 14	8 - 17	12 - 15	13 - 14	9	10 - 15	10 - 15	—	3 - 16
Iron (Fe)	—	.5- .7	.02- .16	.16- 2.2	.2- .6	.02- .4	.08- .5	.02- .26	.02- 2
Calcium (Ca)	3 - 13	7 - 32	3 - 48	3 - 5	8 - 66	1 - 17	8 - 16	27 - 59	27 - 98
Magnesium (Mg)	1 - 10	5 - 23	2 - 32	1 - 7	3 - 47	2 - 7	5 - 9	20 - 30	12 - 39
Sodium and Potassium (Na + K)	145 -180	126 - 450	50 - 274	190 - 266	296 - 391	201 - 322	227 - 520	81 -162	11 - 217
Bicarbonate (HCO_3)	352 -409	388 - 500	268 - 443	262 - 386	337 - 475	355 - 446	387 - 489	338 -348	234 - 371
Sulfate (SO_4)	36 - 67	80 - 373	29 - 215	85 - 236	186 - 510	87 - 221	104 - 453	55 - 87	24 - 332
Chloride (Cl)	15 - 19	33 - 198	11 - 36	24 - 40	104 - 264	20 - 105	79 - 334	58 - 75	17 - 39
Fluoride (F)	.9	.8- 5.4	.1 - 1.8	.5 - 1.4	2.2- 4.9	.4 - 2.5	2.2 - 6	.6 - 1.2	.2 - 1.8
Nitrate (NO_3)	.2- 2.5	.4- 3.5	.4 - 1.5	.4	.4- 3	.04- 3	0 - .4	.4	.4 - 64
Boron (B)	—	—	.4	—	—	—	—	—	—
Dissolved solids	407 -493	495 -1,280	360 - 770	483 - 736	884 -1,440	549 - 890	630 -1,470	467 -527	311 - 760
Total hardness ($CaCO_3$)	12 - 75	36 - 170	18 - 245	17 - 30	34 - 357	3 - 54	40 - 77	152 -272	118 - 398
Percent sodium (percent)	81 - 97	62 - 96	31 - 96	94 - 97	70 - 96	89 - 98	92 - 96	39 - 58	7 - 80
Specific conductance (micromhos at 25°C)	646 -790	825 -2,000	650 -1,181	835 -1,296	1,420 -2,200	815 -1,520	1,030 -2,464	944 -956	554 -1,125
pH	7.9- 8.5	7.4- 7.9	7.5 - 8.4	8.1 - 9.4	7.5- 8.4	7.8 - 9.1	8.1 - 8.4	7.4 - 7.7	7.5 - 8.2
Sodium-adsorption ratio (SAR)	7 - 22	4 - 27	1.4 - 22	18 - 27	9 - 26	15 - 32	15 - 30	2.1 - 4.5	.3 - 8.7

Table 8.—Range of Constituents and Properties of Ground Water From Representative Wells in the Hosston Member of the Travis Peak Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

Hamilton County was not included due to a lack of analyses from wells completed in the Hosston. Refer to ranges from Coryell County, which should closely approximate what one might anticipate in Hamilton County.

CONSTITUENT OR PROPERTY	SOMERVELL COUNTY	JOHNSON COUNTY	ELLIS COUNTY	BOSQUE COUNTY	HILL COUNTY	CORYELL COUNTY	MCLENNAN COUNTY	BELL COUNTY	FALLS COUNTY	MILAM COUNTY	WILLIAMSON COUNTY	TRAVIS COUNTY
Silica (SiO_2)	0 - 15	11 - 13	20	9 - 14	12 - 22	0 - 8	8 - 29	6 - 23	—	—	18	9 - 18
Iron (Fe)	0 - .2	.1- .6	.04- .23	.02- .14	.02- .54	0 - .2	.01- 3.6	0 - .76	.1- .9	.34	.04- 2.8	.02- 3
Calcium (Ca)	24 - 54	1.5- 2.5	2.2 - 14	2.8 - 15	2 - 7	5 - 89	1 - 12	5 - 24	4.8- 83	59	10 - 23	14 - 102
Magnesium (Mg)	22 - 40	.5- .6	1 - 11	1 - 9	.8 - 3	.5- 5	0 - 16	1 - 14	2 - 17	18	6 - 9	3 - 78
Sodium and Potassium (Na + K)	25 - 99	196 -241	299 - 302	136 -204	197 - 467	313 - 435	202 - 350	253 - 632	283 - 510	540	285 - 491	9 - 550
Bicarbonate (HCO_3)	360 -391	400 -432	500 - 556	372 -403	351 - 650	378 - 447	320 - 555	375 - 494	344 - 493	312	400 - 467	247 - 570
Sulfate (SO_4)	20 - 24	63 -129	86 - 287	37 - 83	63 - 260	88 - 201	70 - 140	142 - 493	148 - 740	900	70 - 345	31 - 739
Chloride (Cl)	16 - 27	24 - 37	76 - 111	21 - 35	29 - 174	140 - 415	37 - 175	69 - 528	48 - 91	153	187 - 335	18 - 334
Fluoride (F)	0 - .4	.4- 1.3	1.4 - 1.6	.3 - .5	.3 - 3.2	.4- 2.3	.7 - 3	1 - 4	1.3- 3.7	2.5	2.1 - 3	.5 - 5.3
Nitrate (NO_3)	.4- 1.2	0 - .2	0 - .7	.4 - 1	0 - 1.5	.4- 3	0 - 2.5	0 - 2.5	.4- .6	3	0 - .4	0 - 20
Boron (B)	0 - 1.4	0 - .29	.62- .78	0 - .25	0 - 1.7	—	0 - .4	0 - .8	—	—	—	.07- 6
Dissolved solids	362 -391	497 -632	759 -1,068	405 -531	491 -1,392	765 -1,182	553 - 947	630 -1,711	729 -1,595	1,829	758 -1,410	373 -1,885
Total hardness ($CaCO_3$)	150 -299	6 - 8	10 - 63	8 - 75	9 - 20	14 - 238	5 - 44	22 - 103	19 - 277	222	48 - 93	50 - 500
Percent sodium (percent)	15 - 59	96 - 98	93 - 98	80 - 97	95 - 98	77 - 98	92 - 99	89 - 97	79 - 97	84	91 - 95	5 - 96
Specific conductance (micromhos at 25°C)	640 -652	828 -954	1,270 -1,690	740 -925	826 -2,570	1,230 -2,574	930 -1,568	1,150 -2,600	1,100 -2,822	3,248	2,250 -2,343	632 -3,840
pH	7.7	8.0- 8.3	8.0 - 8.4	8.1 - 8.7	8.2 - 8.9	7.4- 8.7	7.9 - 8.7	7.8- 8.7	7.8- 8.4	7.9	7.9 - 8.2	7.3 - 8.3
Sodium-adsorption ratio (SAR)	.6- 3.5	35 - 38	21 - 41	6.8 - 25	20 - 39	11 - 37	15 - 50	16 - 37	13 - 29	15.8	18 - 27	.2 - 32

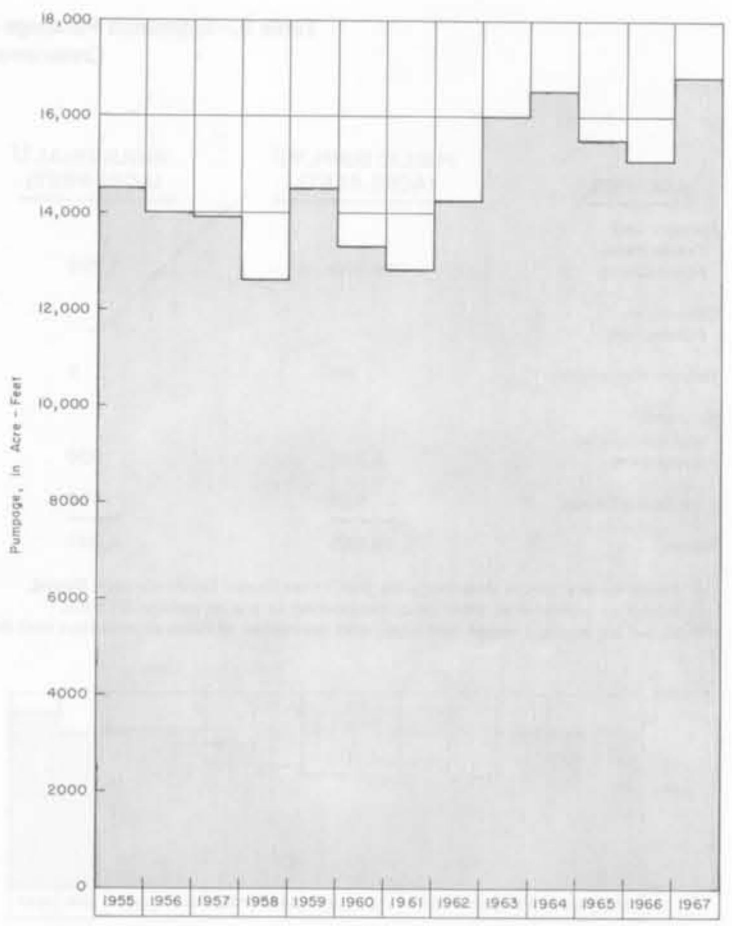

Figure 15

Public Supply Ground-Water Pumpage From the Antlers and Travis Peak Formations in the Study Region, 1955-67

faults. Similarly, transmissibility values were reduced in other areas where the Hensell or Hosston may be affected by shaly facies and where the Hosston is absent at the McGregor High.

Following the assignment of the aquifer coefficients to the respective nodes, the pumping and recharge rates were assigned to each polygon. Recharge was assigned to the outcrop areas in the north and west. The amount of recharge to a particular outcrop polygon was estimated to be approximately 3 percent of the average annual precipitation applied to the outcrop area.

Each aquifer node within the polygons was assigned a percentage of the polygon's recharge and pumping rate. The amount of recharge or pumpage assigned to an aquifer node, located on the outcrop, depended on the following factors: (1) the estimated use of the Hensell and Hosston aquifers within the polygon, (2) the extent of one or both aquifer's outcrop on the surface of the ground, and (3) the amount of recharge and pumpage assigned to the polygon. For example, the Hensell Member outcrops over the entire surface area of a polygon that received an estimated 200 acre-feet of recharge per year. Pumpage from the polygon is estimated to be 50 acre-feet per year from the Hensell and 50 acre-feet per year from the Hosston. Therefore, in this particular polygon the Hensell node would be assigned a net recharge of 150 acre-feet per year and the Hosston node would be assigned a pumpage value of 50 acre-feet per year. The Hensell node would receive the entire recharge since it was the only aquifer that occurred at the surface of the ground.

The first computer studies involved analyzing pumpage and drawdown data from about 1900 to the spring of 1967. For the purposes of this study, it was assumed that in 1900 the aquifers were undeveloped and a zero drawdown condition existed. A water-level map for this period, Figure 39, was constructed from early water-level data presented in the Central Texas area by R. T. Hill (1901). Ground-water pumpage from the Hensell and Hosston aquifers used in the computer studies was estimated

Table 9.—Estimated Pumpage of Ground Water From the Principal Cretaceous Aquifers, 1967

AQUIFER	PUBLIC SUPPLY 1/ (ACRE-FEET)	INDUSTRIAL 1/ (ACRE-FEET)	IRRIGATION 2/ (ACRE-FEET)	RURAL DOMESTIC AND LIVESTOCK 3/ (ACRE-FEET)	TOTALS (ACRE-FEET)
Antlers and Travis Peak Formations	16,800	3,700	16,100	5,900	42,500
Glen Rose Formation	—	—	—	1,200	1,200
Paluxy Formation	60	1	—	1,000	1,061
Edwards and associated limestones	2,100	230	30	930	3,290
Woodbine Group	120	110	—	350	580
Totals	19,080	4,041	16,130	9,380	48,631

1/ Based on water use inventory by the Texas Water Development Board.
2/ Based on power and yield tests conducted in the irrigation district.
3/ Based on average water use rates, and estimates of rural population and livestock taken from the Texas Almanac, 1967.

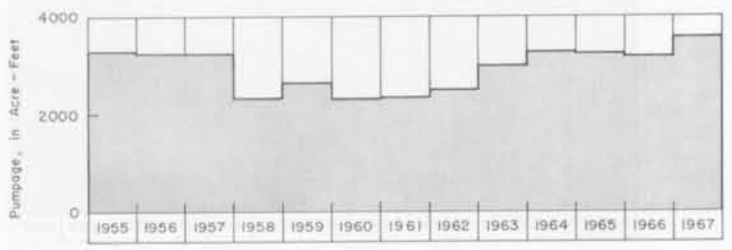

Figure 16

Industrial Ground-Water Pumpage From the Antlers and Travis Peak Formations in the Study Region, 1955-67

from 1900 to 1955. Actual collected pumpage data were used for 1955 through 1966. The objective of the first computer studies was to take the input data (pumpage and aquifer characteristics) and compute water-level declines from 1900 to spring 1967 that would agree with the observed declines illustrated on Figure 42.

Adjustments were made on the input data so that computed declines would reasonably agree with observed declines. Original estimates of pumpage from 1900 to 1955 were increased, and pumpage was assigned to polygons where ground water could have been lost from the aquifers through flowing wells. Additional pumpage was assigned to the Fort Hood well fields to account for ground-water development which could have existed during World War II. All transmissibilities were reduced 25 percent, and additional reductions to transmissibilities were made in the Balcones Fault Zone.

After the final adjustments had been made to these input data, the computer was provided with data on projected pumping rates and programmed to print out water-level declines by aquifer node for the periods spring 1967-1975, spring 1967-1990, and spring 1967-2020. Pumpage figures for these periods were obtained from water resource planning studies conducted by the Board.

Next, it was desirable to know what annual withdrawal or pumping rate would be required for each node and the whole system of nodes, if the Hensell and Hosston water levels were lowered to an interval between 400 and 500 feet below land surface or to the top of the water-bearing sands. The lowering of the water levels would occur from 1967 to 2020 only in the downdip area between the outcrop of the Travis Peak Formation and the base of fresh to slightly saline water of the Hensell and Hosston Members. For the purpose of this study, ground-water development of the Travis Peak in the downdip area was considered economically feasible as long as the 2020 water levels

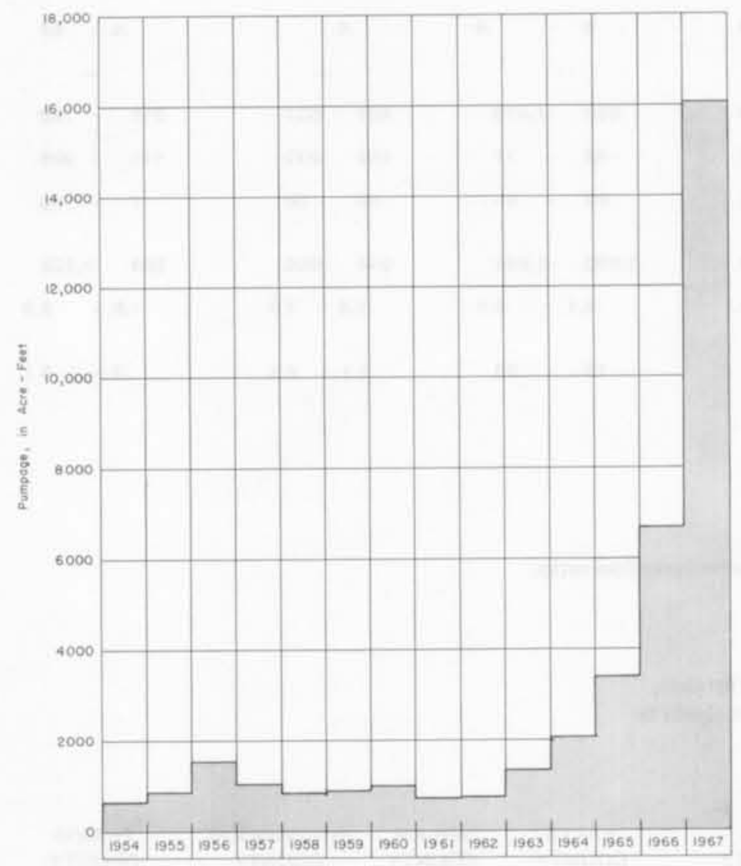

Figure 17

Irrigation Ground-Water Pumpage From the Antlers and Travis Peak Formations in Comanche, Eastland, Erath, and Adjacent Counties, 1954-67

reached no deeper than 400 to 500 feet below land surface or the top of the water-bearing sands.

Before the simulation of the system was begun, the following modifications and assumptions were made:

(1) The annual net recharge or pumpage projected for the 1967 to 2020 period was used in the outcrop nodes.

(2) Annual pumpage was reduced to zero in the Hensell and Hosston nodes in the area downdip from the base of fresh to slightly saline water.

(3) Downdip from the Travis Peak outcrop, annual pumpage was reduced to zero in the Hensell and Hosston nodes where the 1967 water levels were more than 400 feet below land surface or below the top of the water-bearing sands.

After initial simulation was completed, pumpage was modified in nodes occurring in the following areas:

(1) In areas outside the study area but updip from the base of fresh to slightly saline water, the annual pumpage for each node was not used in the final withdrawal total.

(2) In areas 10 miles or less updip from the base of fresh to slightly saline water, the annual pumpage for each node was reduced to avoid large-scale updip movement of saline water.

The results of the simulation provided data on annual pumpage rates for each node which was useful in determining areas most favorable for well development.

Predicted Water-Level Declines

The computer aquifer simulation studies of the Travis Peak Formation indicate that tremendous water-level declines should be expected in several areas of heavy pumpage. The predicted water-level declines for the periods spring 1967-1975, spring 1967-1990, and spring 1967-2020 are presented in the form of water-level decline contour maps for the Hensell and Hosston aquifers, Figures 43 through 48. Based on pumpage projections which were obtained in water resource planning studies conducted by the Board, the maps show large water-level declines in the vicinity of Waco, Belton, Gatesville, Hillsboro, McGregor, and Stephenville. By the year 2020 extensive dewatering of the Hosston aquifer may occur in the Stephenville area, and water-level declines in excess of 1,000 feet may develop in Waco.

The projected water-level declines from spring 1967 to 2020 and the approximate water level above or below the land surface in the spring of 1967 are shown beside the node locations on Figures 45 and 48. An approximation of the predicted 2020 water level below the surface of the ground can be computed from the two values. For example, by the year 2020, the static water level of the Hosston at Meridian should be approximately 301 feet below the surface of the ground.

Ground Water Available for Development

The amount of ground water available from the Hensell and Hosston aquifers in the downdip areas is determined from the computer simulation of pumpage and the associated water-level declines. In 1966, approximately 16,752 acre-feet of ground water was used in the downdip areas for municipal, industrial, and irrigation purposes. The computed optimum node pumping rates show that approximately 40,000 acre-feet of ground water can be pumped annually downdip from the outcrop in the region, excluding the calcareous facies area of the Travis Peak Formation. This proposed annual pumpage represents an approximate increase of 23,248 acre-feet of water over the 1966 municipal, industrial, and irrigation use in the downdip areas, and will not lower the water levels below the 400- to 500-foot interval below land surface or the top of the water-bearing sands until the year 2020. Ground water used by this proposed method of development is obtained from the annual transit recharge and from ground-water storage within the Travis Peak Formation.

Additional quantities of ground water can be developed from the Antlers and Travis Peak Formations in the outcrop areas outside the calcareous facies. These areas receive an estimated 87,150 acre-feet of water as recharge annually, based on approximately 3 percent of the average annual precipitation. The quantity of water that is recharged annually cannot be determined with precision at this time due to lack of adequate data.

In 1966, approximately 6,715 acre-feet of ground water was used in the outcrop areas outside the calcareous facies for municipal, industrial, and irrigation purposes. Allowing for full development in the downdip areas (40,000 acre-feet annually) and the 6,715 acre-feet used in 1966, it appears an additional 40,000 acre-feet can be developed annually under optimum conditions without affecting the downdip availability of ground water from the Travis Peak Formation. In order to develop this additional 40,000 acre-feet annually, all wells must have small capacities and be evenly distributed over the outcrop.

In the computer simulation of the downdip areas of the Travis Peak Formation, an average of 21,269 acre-feet per year for the period 1967 through 2020 was assumed to be pumped in the outcrop area that contributed to the recharge of the Hensell and Hosston aquifers downdip. This area includes the total outcrop of the Antlers and Travis Peak Formations except where dissecting streams prevent the downdip movement of ground water. Therefore under the assumed conditions of recharge, and allowing for maximum ground-water development in the downdip areas, the outcrop areas of the Antlers and Travis Peak Formations should be capable of supplying twice the simulated pumpage for the period 1967 to 2020.

Areas Most Favorable for Future Development

The areas in the study region that are most favorable for future development of ground water from the Travis Peak Formation are shown on Figure 49. The delineations of these areas are a product of the digital computer simulation study of the Travis Peak Formation and are based on an analysis of the optimum node pumping rates which will not lower the water levels below the 400 to 500 foot interval below land surface or the top of the water-bearing sands until the year 2020. The map shows the areas favorable for additional ground-water development in the downdip areas from the Travis Peak Formation, other areas that are fully developed and therefore not suited for additional major development, and other areas that are presently overdeveloped. Also shown is the computer simulated annual pumpage for each area, the 1966 pumpage for each area, and the additional quantity of water that can be developed annually or the annual pumpage which must be reduced if water levels are not to fall below the 400- to 500-foot interval below land surface or below the top of the water-bearing sands.

In the computer simulation of pumpage and associated water-level declines, the simulated pumpage was reduced to zero in the following three general areas: (1) Itasca, Hillsboro, West, McGregor, Gatesville, southwest Waco, and Salado; (2) south of Iredell; and (3) southwest of Georgetown. Although the simulated pumpage was reduced to zero for these areas, the water levels nevertheless declined to depths exceeding 400 to 500 feet below land surface or below the top of the water-bearing sands during the simulation process. These areas, shown on Figure 49, are overdeveloped and unfavorable for ground-water pumpage from the Travis Peak Formation.

The areas around Belton, Dublin, Stephenville, and Waco are shown as overdeveloped areas where the 1966 pumpage would have to be reduced to prevent the water levels from falling below the designated limits. Within these areas some water could be produced, but the amount is less than the 1966 pumpage.

Within the areas unfavorable for additional development, pumpage from the Travis Peak Formation preferably should not be increased beyond the 1966 level of development. The city of Taylor, which is within this zone, for best results should not increase pumpage within the city limits but should plan for distributing the present pumpage and any proposed additional pumpage over a wide area in order to avoid large water-level declines in the immediate vicinity.

The areas most favorable for ground-water development from the Antlers and Travis Peak Formations are located in the east, southeast, west, and northwest portions of the study region. This includes the outcrop not within the calcareous facies of the Travis Peak Formation.

The calcareous facies area should be able to sustain its present ground-water development, which generally consists of small-yield domestic or livestock wells. This area is considered unfavorable for any additional development other than occasional domestic or livestock wells.

In the areas most favorable for future development, the best locations for additional development are the areas where the thickest accumulations of sand containing fresh to slightly saline water occur as shown on Figures 33 and 34. Also, additional development must be distributed widely in order to avoid the deleterious effects of large concentrated withdrawals of ground water in small areas.

Disposal of Salt Water in Areas of Oil and Gas Field Operations

Salt water is produced from oil and gas fields mainly in the northwestern outcrop area of the study region. In this area are numerous oil and gas fields, most of them relatively shallow, ranging from about 500 feet to 4,400 feet in depth. These oil and gas fields have been in operation since the 1920's, and many are still active.

The amounts of brine produced in 1961 and 1967 and the methods of disposal in Brown, Callahan, Comanche, Eastland, and Erath Counties are given in Table 11. The locations of brine-producing areas, amounts of brine produced, methods of disposal, and locations of reported contamination areas are illustrated on Figure 18. The areas of reported contamination are also shown on Figure 35.

Until recently a large amount of salt water produced in connection with oil and gas field operations was disposed of in unlined, open pits that were dug in the loose, porous and permeable sands of the Travis Peak Formation. These pits seldom filled or ran over, and the evaporation rate was not sufficient to account for the large volume of salt water pumped into them. Therefore, in some areas where contamination was reported, the water must have percolated downward into the underlying sands to become incorporated with the native ground water. Comparisons of the relative concentrations of chemical constituents in native ground water, apparently contaminated ground water, and a typical oil-field brine are illustrated on Figure 19.

The recharge and movement of water through the sands is a relatively slow process, and movement may be only a few feet a year. Therefore, in severely affected areas, the water may remain contaminated for many years after the source of contamination has been removed. It is also possible that the contaminated water may migrate downdip, and affect areas that presently contain good native ground water. Periodic checks on the chemical quality of the ground water should be made in order to warn the residents of any possible future contamination.

The Railroad Commission of Texas issued a "no-pit" order effective January 1, 1969, for the entire State. The present method of disposal is generally through wells that inject the salt water into formations that do not contain fresh water.

Pre-Cretaceous Rocks

The occurrence of usable water in the pre-Cretaceous rocks of the study region is generally limited to the area on or adjacent to their respective outcrops. The two most important water-bearing units are the Ellenburger Group of Ordovician age and rocks of Pennsylvanian age.

The principal source of ground water in the Ellenburger Group is precipitation on its outcrop and infiltration from the overlying Travis Peak Formation. Water in the Ellenburger occurs in vugular, cavernous zones and in joints and fractures in the dolomite and limestone beds. Due to this type of occurrence, the hydraulic properties are very unpredictable and extreme variations can occur in short distances. Fluctuations of water levels are usually related to changes in climatic conditions, and to an undetermined amount by pumpage. In and near the outcrop, the chemical quality of the ground water in the Ellenburger is usually of good quality, although very hard. It usually contains less than 1,000 mg/l dissolved solids. However, the quality deteriorates rapidly away from the outcrop, and at distances greater than 20 miles downdip, it is generally unsuitable for

Table 10.—Power-Yield Tests From Selected Irrigation Wells in Comanche, Eastland, and Erath Counties

Method of Distribution: OD, Irrigation well pumps into earthen or concrete tank; D, Irrigation well pumps directly to the field through sprinkler lines; OD-EB, Irrigation well pumps into earthern or concrete tank, and electric booster pumps water from the tank to the field through sprinkler lines.

TEST NO. SHOWN ON FIGURE 38	WELL	DATE OF TEST	METHOD OF DISTRIBUTION	LENGTH OF TEST HOURS	LENGTH OF TEST MINUTES	TOTAL HEAD AT WELL (S) IN FEET	WELL PUMP HORSE-POWER	YIELD AT WELL IN GAL/MIN	TOTAL KWH USED	GALS/ KWH	KWH/ HR	REMARKS
1	JD-30-48-901 JD-30-48-902	August 18, 1967	OD 1/	3	15	53	3 5	37.5 110.0	23.0	1,251	7.1	
2	JD-30-56-103	do.	D 1/	2	00	64	2	25.6	5.5	559	2.8	
3	JD-30-56-401	August 15, 1966	OD 1/	3	30	73	3	40.6	7.0	1,218	2.0	
4	JD-30-56-508	August 16, 1966	D 1/	5	00	126	5	57.5	20.0	863	4.0	
5	JD-30-64-301 JD-30-64-302 JD-30-64-306	August 17, 1966	OD 1/	4	00	60	2 2 3	35.8 47.0 37.5	34.0	849	8.5	
6	JD-30-64-307	do.	D 1/	3	00	201	5	27.8	11.0	455	3.7	
7	JD-31-35-601	July 17, 1967	OD 1/	5	00	35	5	10.4	4.5	693	0.9	
8	JD-31-36-703 JD-31-36-704 JD-31-36-705	July 12, 1967	D 1/	2	30	95	5 5 5	*50.4	37.0	204	14.8	Three wells pumping into one sprinkler line.
9	JP-31-39-502	August 16, 1967	OD 1/	3	10	72	1 3/4	17.7	7.0	480	2.2	
10	JD-31-42-508 JD-31-42-509	August 18, 1966	OD 1/	4	00	45	1 1/2 1	*52.2	11.0	1,139	2.8	Two wells pumping into discharge line.
11	JD-31-42-901 JD-31-42-902	August 19, 1966	OD 1/	4	30	64	2 3	34.3 64.8	26.0	1,029	5.8	
12	JD-31-42-903 JD-31-42-904 JD-31-42-905 JD-31-42-906 JD-31-42-907	do.	D 1/	4	00	118	5 7 1/2 7 1/2 5 7 1/2	*283.7	85.5	796	21.4	Five wells pumping into one sprinkler line.
13	JD-31-43-804 JD-31-43-805	July 10, 1967	D 1/	3	00	159	3 3	*42.1	19.0	399	6.3	Two wells pumping into one sprinkler line.
14	JD-31-43-806 JD-31-43-807 JD-31-43-808	do.	OD 1/	17	30	56	1/2 1 1/2 1 1/2	20.0 45.1 34.9	81.5	1,288	4.7	
15	JD-31-43-904 JD-31-51-306 JD-31-51-307	July 24, 1967	D 1/	3	00	162	7 1/2 7 1/2 3	*174.0	48.0	653	16.0	Three wells pumping into one sprinkler line.
16	JD-31-44-106 JD-31-44-107 JD-31-44-108 JD-31-44-109 JD-31-44-110 JD-31-44-111 JD-31-44-112	August 16, 1967	D 1/	4	00	105	1 1/2 1/2 1 1 3 3	*93.9	72.0	313	18.0	Seven wells pumping into one sprinkler line.
17	JD-31-44-113 JD-31-44-114 JD-31-44-115	August 10, 1967	OD 1/	2	45	114	3 1 1/2 1 1/2	23.6 33.7 29.5	20.0	716	7.3	
18	JD-31-44-403 JD-31-44-404 JD-31-44-405	July 17, 1967	OD 1/	16	30	26	2 2 2	41.2 36.7 55.0	103.0	1,274	6.2	
19	JD-31-44-407 JD-31-44-408 JD-31-44-409	August 14, 1967	D 1/	3	00	181	1 7 1/2 3	*84.8	30.0	509	10.0	JD 31-44-407 pumping into JD 31-44-408. JD 31-44-408 and JD 31-44-409 pumping into one sprinkler line.
20	JD-31-44-503	July 18, 1967	OD 1/	4	00	47	2	59.6	11.0	1,300	2.8	
21	JD-31-44-505	do.	D 1/	4	15	172	7 1/2	87.6	32.0	698	7.5	
22	JD-31-44-506 JD-31-44-507	do.	OD 1/	5	30	66	2 5	44.0 66.0	50.0	726	9.1	
23	JD-31-44-602 JD-31-44-603	August 14, 1967	D 1/	4	00	230	5 5	*140.4	80.0	420	20.0	Two wells pumping into one discharge line.
24	JD-31-44-804 JD-31-44-805	July 11, 1967	OD 1/	3	00	72	2 2	21.3 34.7	13.0	775	4.3	
25	JD-31-44-806	July 18, 1967	OD 1/	20	15	66	3	40.0	45.0	1,080	2.2	
26	JD-31-44-808 JD-31-44-809 JD-31-44-810	August 15, 1967	OD 1/	19	00	68	2 2 2	*66.0	84.0	896	4.4	Three wells pumping into one discharge line.
27	JP-31-48-302	August 16, 1967	D 1/	3	30	206	10	69.1	20.0	726	5.7	
28	JD-31-51-101 JD-31-51-102 JD-31-51-103 JD-31-51-104	August 9, 1967	OD 1/	5	30	55	3 3 1 3/4	*53.2	31.0	566	5.6	Four wells pumping into one discharge line.
29	JD-31-51-224	July 11, 1967	D 1/	6	15	178	7 1/2	56.0	48.0	438	7.7	
30	JD-31-51-225 JD-31-51-226	July 10, 1967	OD 1/	16	00	67	3 3	47.1 61.1	110.5	940	6.9	
31	DY-31-51-605 DY-31-51-606	August 8, 1967	D 1/	4	00	174	5 3	*100.5	33.5	720	8.4	Two wells pumping into one sprinkler line.
32	JD-31-52-102 JD-31-52-103 JD-31-52-104	July 10, 1967	OD 1/	17	00	45	3/4 1/2 1	*48.0	53.0	924	3.1	Three wells pumping into one discharge line.
33	DY-31-52-201 DY-31-52-202 DY-31-52-203	August 17, 1967	OD 1/	23	45	79	2 3 3	12.1 19.5 16.0	173.0	392	7.3	
34	DY-31-52-204 DY-31-52-205	August 10, 1966	D 1/	4	00	133	7 1/2 10	*136.1	55.0	594	13.8	Two wells pumping into one sprinkler line.
35	JP-31-52-301	July 18, 1966	OD 1/	2	00	46	—	142.0	10.0	1,704	5.0	
36	JP-31-52-302 JP-31-52-303	July 10, 1967	OD 1/	4	30	70	3 5	100.0 150.0	42.0	1,607	9.3	
37	JP-31-52-304	July 19, 1966	D 1/	2	00	111	10	120.0	30.0	480	15.0	
38	DY-31-52-401	August 5, 1966	D 1/	3	15	101	7 1/2	114.7	30.0	746	9.2	
39	DY-31-52-502	August 8, 1966	OD 1/	24	00	84	3/4	11.1	46.0	347	1.9	House, barn, and irrigation well on same electrical meter.
40	DY-31-52-608	August 5, 1966	D 1/	5	20	180	15	137.1	85.0	516	16.0	
41	DY-31-52-609	August 8, 1966	D 1/	24	00	161	10	43.6	94.0	668	3.9	House and domestic well on same electrical meter. Domestic well pumping into irrigation well.
42	DY-31-52-611 DY-31-52-612 DY-31-52-613	August 17, 1967	D 1/	24	05	90	3 5 3	*100.0	243.0	595	10.1	Three wells pumping into one sprinkler line.
43	DY-31-52-703	June 28, 1966	OD 1/	2	00	61	1	27.0	3.0	1,080	1.5	
44	DY-31-52-704 DY-31-52-705 DY-31-52-706	August 5, 1966	D 1/	6	00	150	5 5 5	*86.4	74.0	420	12.3	Three wells pumping into one sprinkler line.
45	DY-31-52-804 DY-31-52-805 DY-31-52-806	August 15, 1967	D 1/	17	35	119	10 15 10	*212.6	460.0	488	26.2	Three wells pumping into one sprinkler line.
46	DY-31-52-902	August 8, 1966	D 1/	4	00	151	7 1/2	102.3	32.0	767	8.0	
47	JP-31-53-202	July 14, 1966	OD 1/	16	00	67	5	67.0	53.0	1,214	3.3	
48	JP-31-53-203	do.	OD 1/	5	00	—	7 1/2	137.0	44.0	934	8.8	
49	JP-31-53-403	do.	D 1/	7	00	84	20	212.0	140.0	636	20.0	
50	JP-31-53-411 JP-31-53-412	July 10, 1967	D 1/	5	45	—	15 20	*258.4	195.0	457	33.9	Two wells pumping into one sprinkler line.
51	JP-31-53-503	July 12, 1966	OD 1/	2	00	103	5	57.0	9.0	760	4.5	
52	DY-31-53-702 DY-31-53-703	July 29, 1966	OD 1/	4	00	105	3 3	33.3 28.5	20.0	742	5.0	
53	DY-31-53-704 DY-31-53-705	do.	OD-EB 1/	5	00	99	5 5	72.7 72.7	82.0	532	16.4	15-HP booster pump; yield at sprinklers 199.0 gpm. Two irrigation wells pumped 5 hours. Booster pumped 3 hours, 40 minutes.
54	DY-31-53-706	do.	D 1	4	00	128	5	30.4	13.0	561	3.3	
55	JP-31-53-717 JP-31-53-718	July 12, 1966	OD 1	5	00	87	1 1/2 1	29.6 30.0	18.0	993	3.6	
56	DY-31-53-724 DY-31-53-725	August 5, 1966	OD 1/	6	50	74	1 1	10.9 8.3	23.0	342	3.4	
57	JP-31-53-732	July 7, 1967	D 1/	5	00	211	7 1/2	93.1	48.0	582	9.6	
58	JP-31-53-733 JP-31-53-734	July 6, 1967	D 1/	4	00	201	7 1/2 5	*92.5	64.0	347	16.0	Two wells pumping into one sprinkler line.
59	JP-31-53-804 JP-31-53-806 JP-31-53-808	do.	OD-EB 1/	7	30	120	— — 7 1/2	33.0 71.0 99.0	173.0	528	23.1	Booster pump yield at sprinklers 293 gpm. Three irrigation wells pumped 7 hours, 30 minutes. Booster pumped 5 hours, 40 minutes.
60	JP-31-53-806	July 12, 1966	OD 1/	12	00	70	—	56.0	40.0	1,008	3.3	
61	JP-31-53-808	July 6, 1967	OD 1/	5	15	158	7 1/2	99.0	37.0	843	7.0	
62	JP-31-53-809	July 7, 1967	D 1/	5	00	225	5	94.5	55.0	515	11.0	
63	JP-31-54-801	July 17, 1967	OD 2/	18	00	—	30	200.0	510.0	424	28.3	

See footnotes at end of table.

Table 10.—Power-Yield Tests From Selected Irrigation Wells in Comanche, Eastland, and Erath Counties—Continued

TEST NO. SHOWN ON FIGURE 38	WELL	DATE OF TEST	METHOD OF DISTRIBUTION	LENGTH OF TEST HOURS	LENGTH OF TEST MINUTES	TOTAL HEAD AT WELL (S) IN FEET	WELL PUMP HORSE-POWER	YIELD AT WELL IN GAL/MIN	TOTAL KWH USED	GALS/ KWH	KWH/ HR	REMARKS
64	JP-31-55-201	July 12, 1967	OD 2/	9	45	—	20	120.0	270.0	260	27.7	
65	JP-31-55-403	July 18, 1967	D 2/	4	00	406	30	150.4	155.0	233	38.8	
66	JP-31-55-407	July 17, 1967	OD 2/	17	05	325	25	171.5	410.0	429	24.0	
67	JP-31-55-803	August 15, 1967	OD 2/	23	00	282	20	184.6	535.0	476	23.3	House, barn, and irrigation well on same electrical meter.
68	DY-31-57-604	August 9, 1966	D 1/	4	00	160	10	73.5	37.0	477	9.3	
69	DY-31-58-703	do.	OD 1/	4	00	66	3	43.4	8.5	1,226	2.1	
70	DY-31-59-301 DY-31-59-307	August 11, 1966	D 1/	4	00	253	15 10	*132.0	80.0	396	20.0	Two wells pumping into one sprinkler line.
71	DY-31-59-305 DY-31-59-306	July 28, 1966	OD 1/	4	00	50	2 1 1/2	23.1 18.1	16.0	618	4.0	
72	DY-31-60-209 DY-31-60-210	August 16, 1966	OD 1/	25	00	87	3 2	72.7 64.8	190.0	1,086	7.6	House, barn, and irrigation wells on same electrical meter.
73	DY-31-60-212	August 15, 1966	D 1/	12	05	152	3	35.8	41.0	633	3.4	
74	DY-31-60-502	July 28, 1966	OD 1/	4	10	75	3/4	26.3	4.0	1,644	1.0	
75	DY-31-60-605	August 15, 1967	OD 1/	24	08	71	3	36.1	79.0	662	3.3	
76	DY-31-60-607	do.	OD 1/	23	40	86	3	48.7	84.0	823	3.5	
77	DY-31-60-608	do.	OD-EB 1/	23	38	73	3	66.5	258.0	365	11.0	15-HP booster pump (off each day about 8 hours).
78	DY-31-60-701	July 25, 1967	OD 1/	4	00	41	1 1/2	34.7	7.5	1,110	1.9	
79	DY-31-60-809	do.	OD 1/	4	30	61	3	64.7	17.0	1,028	3.8	
80	DY-31-60-810	do.	OD 1/	4	30	55	1 1/2	35.9	8.0	1,212	1.8	
81	DY-31-60-811 DY-31-60-812	do.	D 1/	5	00	128	10 5	*135.0	55.0	736	11.0	Two wells pumping into one sprinkler line.
82	DY-31-61-109 DY-31-61-110 DY-31-61-111	August 10, 1966	D 1/	4	20	170	3 3 5	*160.0	59.0	705	13.7	Three wells pumping into one sprinkler line.
83	DY-31-61-112 DY-31-61-113 DY-31-61-114	August 16, 1967	OD-EB 1/	24	00	62	1 2 2	21.2 41.1 33.4	336.0	410	14.0	
84	DY-31-61-115 DY-31-61-116 DY-31-61-117	do.	OD 1/	22	40	62	1 2 7 1/2	17.2 42.9 68.6	228.0	768	10.1	
85	JP-31-61-301	July 13, 1966	D 1/	5	00	121	20	173.0	90.0	577	18.0	
86	DY-31-61-402 DY-31-61-403	June 29, 1966	OD 1/	7	00	102	3 1 1/2	57.0 29.0	35.0	1,032	5.0	
87	JP-31-61-601	July 12, 1967	OD 2/	24	00	—	10	64.8	380.0	246	15.8	House, barn, and irrigation well on same electrical meter.
88	DY-31-61-701	August 3, 1966	D 1/	4	00	249	10	90.0	32.0	675	8.0	
89	DY-31-61-703	do.	OD 1/	4	00	159	5	80.0	21.0	914	5.3	
90	DY-31-61-802	do.	OD 1/	25	10	105	7 1/2	114.3	193.0	894	7.7	Barn, livestock, and irrigation well on same electrical meter.
91	DY-31-61-901	July 27, 1966	OD 1/	3	30	104	3	58.5	12.0	1,024	3.4	
92	JP-31-62-501	July 17, 1967	OD 2/	23	10	250	5	48.0	153.0	436	6.6	House, barn, and irrigation well on same electrical meter.
93	JP-32-41-103	August 17, 1967	OD 1/	5	10	110	5	120.0	30.0	1,240	5.8	
94	DY-41-03-101	August 7, 1967	OD 1/	18	00	55	5	41.1	42.0	1,057	2.3	
95	DY-41-03-203	July 26, 1967	OD 1/	3	00	39	1 1/2	29.7	6.0	891	2.0	
96	DY-41-04-201 DY-41-04-202 DY-41-04-203	August 7, 1967	OD 1/	18	15	74	1 1/2 1 1	51.6 12.2 30.0	110.5	930	6.1	
97	DY-41-04-204 DY-41-04-205 DY-41-04-206	July 25, 1967	D 1/	3	15	139	2 2 2	*74.0	22.5	641	6.9	Three wells pumping into one sprinkler line.
98	DY-41-04-502	June 29, 1966	OD 1/	5	00	94	5	67.0	18.0	1,117	3.6	
99	DY-41-04-505 DY-41-04-506	August 4, 1966	D 1/	4	00	192	5 7 1/2	*67.5	42.0	386	10.5	

See footnotes at end of table.

Table 10.—Power-Yield Tests From Selected Irrigation Wells in Comanche, Eastland, and Erath Counties—Continued

TEST NO. SHOWN ON FIGURE 38	WELL	DATE OF TEST	METHOD OF DISTRIBUTION	LENGTH OF TEST HOURS	LENGTH OF TEST MINUTES	TOTAL HEAD AT WELL (S) IN FEET	WELL PUMP HORSE-POWER	YIELD AT WELL IN GAL/MIN	TOTAL KWH USED	GALS/ KWH	KWH/ HR	REMARKS
100	DY-41-05-205 DY-41-05-212 DY-41-05-213	August 2, 1966	OD-EB 1/	8	36	115	3 3 7 1/2	34.4 50.0 100.0	210.0	453	24.4	20-HP booster pump; yield at sprinklers 251.3 gpm. Three irrigation wells pumped 8 hours, 36 minutes. Booster pumped 6 hours, 20 minutes.
101	DY-41-05-206	June 21, 1966	OD 1/	3	00	102	5	71.0	14.5	881	4.8	
102	DY-41-05-207	do.	OD 1/	3	00	—	5	51.0	10.5	874	3.5	
103	DY-41-05-210 DY-41-05-211	August 2, 1966	D 1/	4	45	229	5 5	*45.2	30.0	429	6.3	
104	DY-41-05-502	do.	OD 1/	12	00	86	5	56.5	49.0	830	4.1	
105	DY-41-05-503	do.	OD 1/	4	00	86	7 1/2	218.1	27.0	1,939	6.8	
106	DY-41-05-905	July 27, 1966	OD 1/	4	15	123	5	60.0	20.0	765	4.7	
107	DY-41-12-303	July 12, 1966	OD 1/	14	45	135	7 1/2	95.7	85.0	996	5.8	
108	DY-41-12-304	June 21, 1966	D 1/	2	00	101	10	69.8	16.0	524	8.0	
109	DY-41-13-101	August 4, 1966	OD 1/	6	30	126	7 1/2	92.3	40.0	900	6.2	
110	DY-41-13-201 DY-41-13-202	August 8, 1967	OD 1/	5	00	152	3 3	30.0 21.3	25.0	616	5.0	
111	DY-41-14-106 DY-41-14-107	August 4, 1966	OD 1/	4	00	175	5 15	30.0 53.3	50.0	400	12.5	
112	DY-41-14-305	August 8, 1967	D 1/	3	15	115	7 1/2	96.7	18.5	1,019	5.7	
Power-yield test averages			OD 1/	9	02	80		75.7	45.1	959	4.8	
			OD 2/	19	10	286		131.5	376.3	379	20.9	
			D 1/	5	34	156		104.4	65.4	569	11.6	
			D 2/	4	00	406		150.4	155.0	233	38.8	
			OD-EB 1/	13	44	94		139.0	211.8	458	17.8	

1/ Lowlift, where irrigation water is produced from the Travis Peak Formation and also distributed onto the outcrop of the Travis Peak Formation.
2/ Highlift, where irrigation water is produced from the Travis Peak Formation and distributed onto the outcrop of the Paluxy Formation.
* Combined yield of wells.

domestic use. The development of the Ellenburger as an aquifer is small and occurs only in the extreme west-central part of the study region in Burnet and Lampasas Counties. The city of Burnet obtains most of its water supply from the Ellenburger or the hydrologically connected San Saba Member. Several domestic and livestock wells also produce from the Ellenburger. The Ellenburger in this outcrop area is probably capable of future development, both for public supply and domestic and livestock use. However, due to the occurrence of water in vugs and cavernous zones, extensive test drilling may be necessary to locate the permeable and porous zones.

The other important water-bearing unit is the rocks of Pennsylvanian age. Precipitation on the outcrop of these rocks and infiltration from the overlying Travis Peak Formation are the major sources of ground water. Usable quality water is generally found in saturated sandstones and conglomerates in or near the outcrop. Wells producing from rocks of Pennsylvanian age in the study region are usually capable of only small yields, but locally the capacity may be moderate to large. The chemical quality of the water is usually good in the area on or adjacent to the outcrop, but becomes increasingly mineralized downdip from the outcrop. In some local areas the Pennsylvanian is the primary source of water, particularly in the vicinity of Lampasas, which obtains its public supply from springs that issue from Pennsylvanian rocks. In the vicinity of Duster in Comanche County, irrigation wells produce usable quality water from the Pennsylvanian, and many domestic and livestock wells produce from the Pennsylvanian in and near its outcrop.

The potential development of ground water from rocks of Pennsylvanian age cannot be estimated with existing data. Future detailed studies are necessary to fully evaluate these rocks as an aquifer.

The Cotton Valley Group of Jurassic age, if present, may yield potable water. However, the amounts and quality are unknown.

Glen Rose Formation

Most of the water in the Glen Rose Formation occurs under weak artesian conditions because of the many shale beds which act as confining layers for the water-bearing limestone beds. In these limestone beds, the water is contained in solution channels, joints, and fractures; however, occasionally water is found in locally occurring sand lenses. The Glen Rose is recharged by infiltration of rainfall, by seepage from lakes and streams, and possibly by seepage from the overlying Paluxy Formation. Downdip movement of ground water in the Glen Rose is generally east or southeast, although variations occur due to the solution channels. The Glen Rose discharges water naturally by springs, seeps, and vertical seepage to underlying beds; and artificially by wells. The hydraulic properties of the Glen Rose are generally undetermined due to lack of data and the many variations that occur in limestone aquifers. Water levels in the Glen Rose fluctuate in relation to climatic changes and pumpage. Many Glen Rose wells are known to have gone dry during periods of extended or severe drought.

The chemical quality of ground water in the Glen Rose is usually rated as slightly saline (1,000 to 3,000 mg/l dissolved solids) in and near the outcrop area. The quality deteriorates downdip from the outcrop because of restricted circulation and possibly because of an increase in the evaporite beds occurring in the Glen Rose. In the outcrop and adjacent areas, Glen Rose water is generally very hard, often high in sulfate, chloride, and sodium content, and usually exceeds the standards of the U.S. Public Health Service. However, it is used in many rural areas and no ill effects have been noticed, except in some areas where excessive fluoride has caused teeth to become mottled. In the downdip area, the Glen Rose becomes highly mineralized and is a potential source of contamination to wells that drill through the Glen Rose to the underlying Travis Peak Formation. Extreme caution should be taken and every effort made to completely case off the Glen Rose when completing a well in the Travis Peak Formation in order to prevent contamination and obtain higher quality water from the Travis Peak. Ranges of constituents or properties of ground water from the Glen Rose Formation are presented in Table 12.

The Glen Rose is used almost exclusively as a domestic and livestock supply. The formation is relatively shallow and wells require little or no casing, making this source of water economically attractive to small farms and ranches. Most of the Glen Rose wells are located in the west-central part of the study region, and the area where usable quality ground water is potentially available occurs in all or parts of the following counties: Bell, Bosque, Brown, Burnet, Comanche, Coryell, Erath, Hamilton, Lampasas, Mills, Somervell, Travis, and Williamson. The estimated amount of water used from the Glen Rose in 1967 was 1,200 acre-feet, all of which was used entirely for domestic and livestock purposes.

Paluxy Formation

The Paluxy Formation occurs as an aquifer in the northern and central part of the study region, generally south and east of the Bosque River and east of the Leon River. This area is illustrated on Figure 50, which shows the approximate thickness of sand containing fresh to slightly saline water in the Paluxy. In this area, most of the water occurs where the sands are 15 feet thick or more, however, some small-yield wells occur where the sands are thinner than 15 feet.

Ground water in the Paluxy occurs in saturated sand beds under both water-table and artesian conditions. Water-table conditions dominate the outcrop area and artesian conditions prevail in the downdip areas.

The recharge to the Paluxy occurs in its outcrop from the infiltration of rainfall and seepage from streams flowing over the outcrop. The sandy, permeable soil and vegetative cover of the Paluxy are favorable for recharge and are probably capable of receiving more recharge than the aquifer is capable of transmitting.

The movement of water in the Paluxy is generally downdip and at right angles to the strike of the beds, however, this movement is modified because the valleys of Cowhouse Creek and Bosque, Lampasas, and Leon Rivers have cut through the entire Paluxy Formation in a large area of the study region. The general direction of movement and the influence of the stream valleys are illustrated on Figure 51, which also shows the approximate piezometric surface of the Paluxy. The hydraulic gradient is about 20 feet per mile in the outcrop and adjacent areas, decreasing to about 12 feet per mile in the downdip area where artesian conditions exist. The general direction of movement is eastward, except in the Hillsboro area where a cone of depression causes water to move into this area from all directions. The hydraulic gradient and cone of depression are also illustrated on Figure 51.

Discharge from the Paluxy occurs naturally as springs and seeps, particularly along the many valleys dissecting the area. Pumpage of wells constitutes most of the water artificially discharged from the aquifer.

No aquifer tests were conducted in wells completed in the Paluxy Formation. Coefficients of transmissibility, determined from specific capacities obtained from water well drilling contractors, range from 0 to 2,500 gpd/ft. The average coefficient of transmissibility in the region is about 1,000 gpd/ft. The low transmissibilities are attributed to thin or shaly sand sections. Higher transmissibilities occur in the cleaner and thicker sand sections. Figure 50 shows the actual net amount of sand, excluding shale, that occurs in the Paluxy. In areas of the thickest sand accumulation, such as the northeastern area, the transmissibility will be the highest. Aquifer tests should be conducted in the Paluxy in order to accurately determine the transmissibility and permeability of the aquifer.

Water levels fluctuate seasonally as indicated by the periodic measurements in a number of observation wells completed in the Paluxy Formation. These measurements show that the highest water levels occur in the spring and the lowest in the fall. The predominant cause of fluctuations in water levels is pumpage from the formation. Due to the low transmissibility of the Paluxy, any prolonged moderate to heavy pumpage will result in a fairly rapid decline of the water level, particularly in the immediate area. A gradual decline of the water level has probably occurred in the Paluxy, however, due to a lack of historical water-level measurements, the rate of decline is undetermined. If

Table 11.—Reported 1961 and 1967 Brine Production and Disposal in Brown, Callahan, Comanche, Eastland, and Erath Counties

(Quantities reported in barrels)

Production and method of disposal taken from Railroad Commission of Texas, 1961 and 1967 salt water production and disposal questionnaires.

AREA SHOWN ON FIGURE 18	YEAR	COUNTY	DISPOSAL IN PITS	DISPOSAL IN INJECTION WELLS	OTHER DISPOSAL	TOTAL BRINE PRODUCTION
K-1	1961	Callahan	45,192	899,331	2,625	947,148
	1967	Callahan	36	566,809	4,380	571,225
K-2	1961	Callahan	2,280	10,950	0	13,230
	1967	Callahan	0	12,775	0	12,775
K-3	1961	Callahan	14,057	380,021	0	394,078
		Eastland	168,255	28,470	0	196,725
		Subtotals	182,312	408,491	0	590,803
	1967	Callahan	3	66,158	0	66,161
		Eastland	0	112,368	0	112,368
		Subtotals	3	178,526	0	178,529
K-4	1961	Callahan	11,251	0	4,200	15,451
		Eastland	1,927	6,570	0	8,497
		Subtotals	13,178	6,570	4,200	23,948
	1967	Callahan	72	5,030	0	5,102
		Eastland	0	12,957	0	12,957
		Subtotals	72	17,987	0	18,059
K-5	1961	Eastland	32,462	14,600	0	47,062
	1967	Eastland	1,140	5,840	365	7,345
K-6	1961	Brown	12,166	0	0	12,166
		Comanche	5,721	128,625	0	134,346
		Eastland	55,356	0	0	55,356
		Subtotals	73,243	128,625	0	201,868
	1967	Brown	3,185	0	0	3,185
		Comanche	7,771	0	0	7,771
		Eastland	3,174	7,300	0	10,474
		Subtotals	14,130	7,300	0	21,430
K-7	1961	Eastland	54,109	0	3,650	57,759
	1967	Eastland	0	153,513	0	153,513
K-8	1961	Eastland	104,394	1,515,015	0	1,619,409
	1967	Eastland	80,190	1,357,098	0	1,437,288
K-9	1961	Erath	10,950	0	0	10,950
	1967	Erath	8,688	19,356	0	28,044
K-10	1961	Comanche	3,926	0	0	3,926
		Eastland	33,772	2,555	0	36,327
		Erath	3,285	0	0	3,285
		Subtotals	40,983	2,555	0	43,538
	1967	Comanche	291	0	0	291
		Eastland	20,088	17,141	0	37,229
		Erath	1,174	0	0	1,174
		Subtotals	21,553	17,141	0	38,694
K-11	1961	Comanche	2,032	0	474	2,506
	1967	Comanche	152	0	0	152
K-12	1961	Brown	92,944	521,215	9,855	624,014
	1967	Brown	9,086	444,123	0	453,209
K-13	1961	Comanche	800	0	0	800
	1967	Comanche	0	0	0	0
Total brine production and disposal on or immediately adjacent to the outcrop of Cretaceous rocks	1961	Brown	105,110	521,215	9,855	636,180
		Callahan	72,780	1,290,302	6,825	1,369,907
		Comanche	12,479	128,625	474	141,578
		Eastland	450,275	1,567,210	3,650	2,021,135
		Erath	14,235	0	0	14,235
		Totals	654,879	3,507,352	20,804	4,183,035
	1967	Brown	12,271	444,123	0	456,394
		Callahan	111	650,772	4,380	655,263
		Comanche	8,214	0	0	8,214
		Eastland	104,592	1,666,217	365	1,771,174
		Erath	9,862	19,356	0	29,218
		Totals	135,050	2,780,468	4,745	2,920,263

the aquifer is developed to any extent in the future, a general decrease in the water level is inevitable. The approximate altitude of water levels in wells completed in the Paluxy in 1967 and 1968 is shown on Figure 51.

The water in the Paluxy Formation is usually a soft, sodium bicarbonate type in the downdip areas and a hard, calcium bicarbonate type in the outcrop. The water is usually of good quality, except in the extreme downdip areas where it becomes

Table 11.—Reported 1961 and 1967 Brine Production and Disposal in Brown, Callahan, Comanche, Eastland, and Erath Counties—Continued

AREA SHOWN ON FIGURE 18	YEAR	COUNTY	DISPOSAL IN PITS	DISPOSAL IN INJECTION WELLS	OTHER DISPOSAL	TOTAL BRINE PRODUCTION
P-1	1961	Callahan	6,939	1,114,187	365	1,121,491
	1967	Callahan	13,378	2,572,291	0	2,585,669
P-2	1961	Callahan	5,340	157,222	0	162,562
	1967	Callahan	0	88,177	0	88,177
P-3	1961	Callahan	93,533	1,746,922	3,087	1,843,542
		Eastland	122,131	304,426	4,185	430,742
		Subtotals	215,664	2,051,348	7,272	2,274,284
	1967	Callahan	4	2,939,576	0	2,939,580
		Eastland	2,191	614,692	28,250	645,133
		Subtotals	2,195	3,554,268	28,250	3,584,713
P-4	1961	Brown	263,038	119,005	6,825	388,868
		Callahan	46,240	859,075	1,823	907,138
		Subtotals	309,278	978,080	8,648	1,296,006
	1967	Brown	12,896	488,529	0	501,425
		Callahan	0	2,045,232	0	2,045,232
		Subtotals	12,896	2,533,761	0	2,546,657
P-5	1961	Brown	11,670	32,850	0	44,520
	1967	Brown	365	34,675	0	35,040
P-6	1961	Eastland	4,127	0	0	4,127
	1967	Eastland	2,932	0	0	2,932
P-7	1961	Eastland	701	0	0	701
	1967	Eastland	1,061	0	0	1,061
P-8	1961	Eastland	83,486	90,459	0	173,945
	1967	Eastland	109,500	61,468	7,036	178,004
P-9	1961	Eastland	557	0	0	557
	1967	Eastland	0	0	0	0
Total brine production and disposal on the outcrop of Pennsylvanian and Permian rocks	1961	Brown	274,708	151,855	6,825	433,388
		Callahan	152,052	3,877,406	5,275	4,034,733
		Eastland	211,002	394,885	4,185	610,072
		Totals	637,762	4,424,146	16,285	5,078,193
	1967	Brown	13,261	523,204	0	536,465
		Callahan	13,382	7,645,276	0	7,658,678
		Eastland	115,684	677,160	35,286	827,130
		Totals	114,327	8,844,660	35,286	9,022,273
Total brine production in all areas, and counties	1961	Brown	379,818	673,070	16,680	1,069,568
		Callahan	224,832	5,167,708	12,100	5,404,640
		Comanche	12,479	128,625	474	141,578
		Eastland	661,277	1,962,095	7,835	2,631,207
		Erath	14,235	0	0	14,235
		Totals	1,292,641	7,931,498	37,089	9,261,228
	1967	Brown	25,532	967,327	0	992,859
		Callahan	13,493	8,296,048	4,380	8,313,921
		Comanche	8,214	0	0	8,214
		Eastland	220,276	2,342,377	35,651	2,598,304
		Erath	9,862	19,356	0	29,218
		Totals	277,377	11,625,108	40,031	11,942,516

increasingly mineralized. The area where the water in the Paluxy contains less than 3,000 mg/l dissolved solids is illustrated on Figure 50, however, local conditions within this area may cause the dissolved solids to exceed 3,000 mg/l. In most places inside this area, the quality of water is within the recommended limits established by the U.S. Public Health Service, except for dissolved-solids content which often exceeds 500 mg/l. The water from the Paluxy is generally acceptable for public supply and industrial purposes. In the outcrop area it is suitable for irrigation, but downdip it has a high to very high sodium hazard. The ranges of constituents and properties of ground water in the Paluxy are presented in Table 13.

The Paluxy in the study region is used primarily as a source of water for domestic and livestock purposes. A few small towns and communities obtain their water supplies from the Paluxy, and Hillsboro has wells that are triple completed in the Woodbine Group, Paluxy Formation, and Travis Peak Formation. Total estimated pumpage from the Paluxy in the region in 1967 was 1,061 acre-feet. Rural domestic and livestock use was 1,000 acre-feet, public supply was 60 acre-feet, and industries used one acre-foot. This estimated use, as compared with the other aquifers, is shown in Table 9. Most of this pumpage occurs in Bosque, Coryell, Erath, Hamilton, Hill, and Somervell Counties. There is no extensive development of the Paluxy, except for the many scattered domestic and livestock wells. The city of Hillsboro is the largest single user of water from the Paluxy.

The amount of water available for development from the Paluxy was estimated by using the following assumptions: (1) the effect of pumping is such that the static water level is drawn down to the top of the aquifer, (2) the top of the aquifer is 400 feet below land surface, and (3) the line along the top of the aquifer at this 400-foot depth is roughly parallel to the outcrop.

In determining the quantity of water available, the following were calculated: (1) the total amount of water obtained from storage by lowering the static water level to the top of the aquifer where this depth is 400 feet below land surface, and (2) the amount of water that the aquifer will transmit annually, after the static water level has been lowered to 400 feet below the land surface.

The total amount of water available from storage was determined by calculating the volume affected when the static water level is lowered from its 1967 level to a proposed level 400 feet below the land surface. This volume is multiplied by the estimated coefficient of storage and then converted to acre-feet. For the Paluxy Formation, the area considered in determining this amount is east of the outcrop along the Bosque and Leon Rivers and north of U.S. Highway 84. The total amount of water available from storage is calculated to be approximately 28,440 acre-feet. This amount can be pumped from storage only once, not annually, and should not be considered in long-range planning.

The amount of water that the aquifer will transmit annually was computed by using the formula

$$Q = TIW,$$

where Q is the quantity of water in gallons per day moving through the aquifer; T is the coefficient of transmissibility in gallons per day per foot; I is the gradient of the top of the aquifer in feet per mile, and is equal to the hydraulic gradient when the static water level is lowered to the top of the aquifer where it is 400 feet below land surface; and W is the width of the aquifer in miles normal to the gradient. Using this formula and the area previously described, the amount of water moving through the Paluxy in the study region was computed to be approximately 930 acre-feet per year. This is the amount that can be pumped annually without lowering the static water level below the top of the aquifer or below 400 feet below land surface. If pumpage exceeds this amount, the water level will decline below the top of the aquifer. If the pumpage is less than this amount, water will be returned to storage, and the water level will rise above the top of the aquifer.

Recharge to the Paluxy appears to be more than adequate to supply the 930 acre-feet per year that the aquifer is capable of transmitting. The outcrop of the Paluxy within the area considered is approximately 91,900 acres. Therefore, only about 0.13 inch of precipitation, or about 0.4 percent of the average annual precipitation of 32 inches, is needed as recharge to supply the 930 acre-feet that the aquifer is capable of transmitting. It is apparent that under these conditions the outcrop receives more recharge than can be transmitted and the excess will be discharged in the outcrop by natural means.

In 1967, approximately 1,061 acre-feet of water was pumped from the Paluxy, however, some of this was west and south of the area considered above in computing the amount available. It is estimated that the amount of water pumped from the Paluxy is almost the same as the amount it is capable of transmitting, and consequently, any future development will remove water from storage and cause declines in water levels.

Future development of the Paluxy in the region appears to be limited by the relatively thin sand and low transmissibilities. The best areas for development are those where the net sand thickness is 35 feet or more. These areas are illustrated on Figure 50 and generally occur in northern Bosque, southeastern Erath, northeastern Hill, and southern Somervell Counties. The specific capacities in this area are generally 1.0 gpm/ft of drawdown or less; therefore, even moderate yields will cause large drawdowns in water levels. Consequently, only small yields of 100 gpm or less can be expected in this area.

A more complete and detailed ground-water investigation of the Paluxy Formation is needed in order to fully evaluate the amount and quality of water available for development.

Edwards and Associated Limestones

The Edwards and associated limestones exist as a continuous aquifer only in the southeastern part of the study region, generally south of the Leon River in Bell County and along

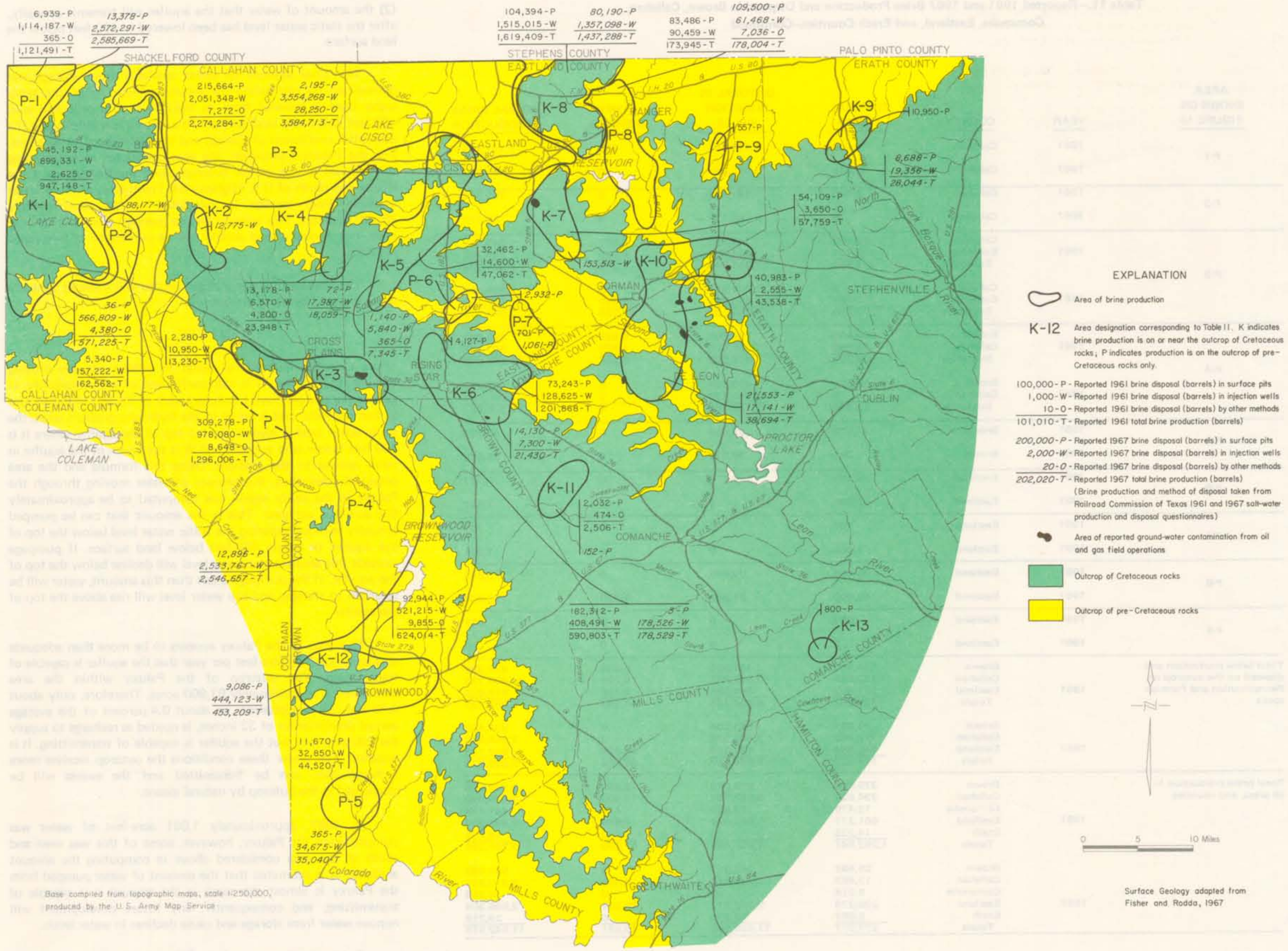

Figure 18

Location and Amounts of Reported 1961 and 1967 Brine Production and Disposal in Brown, Callahan, Comanche, Eastland, and Erath Counties

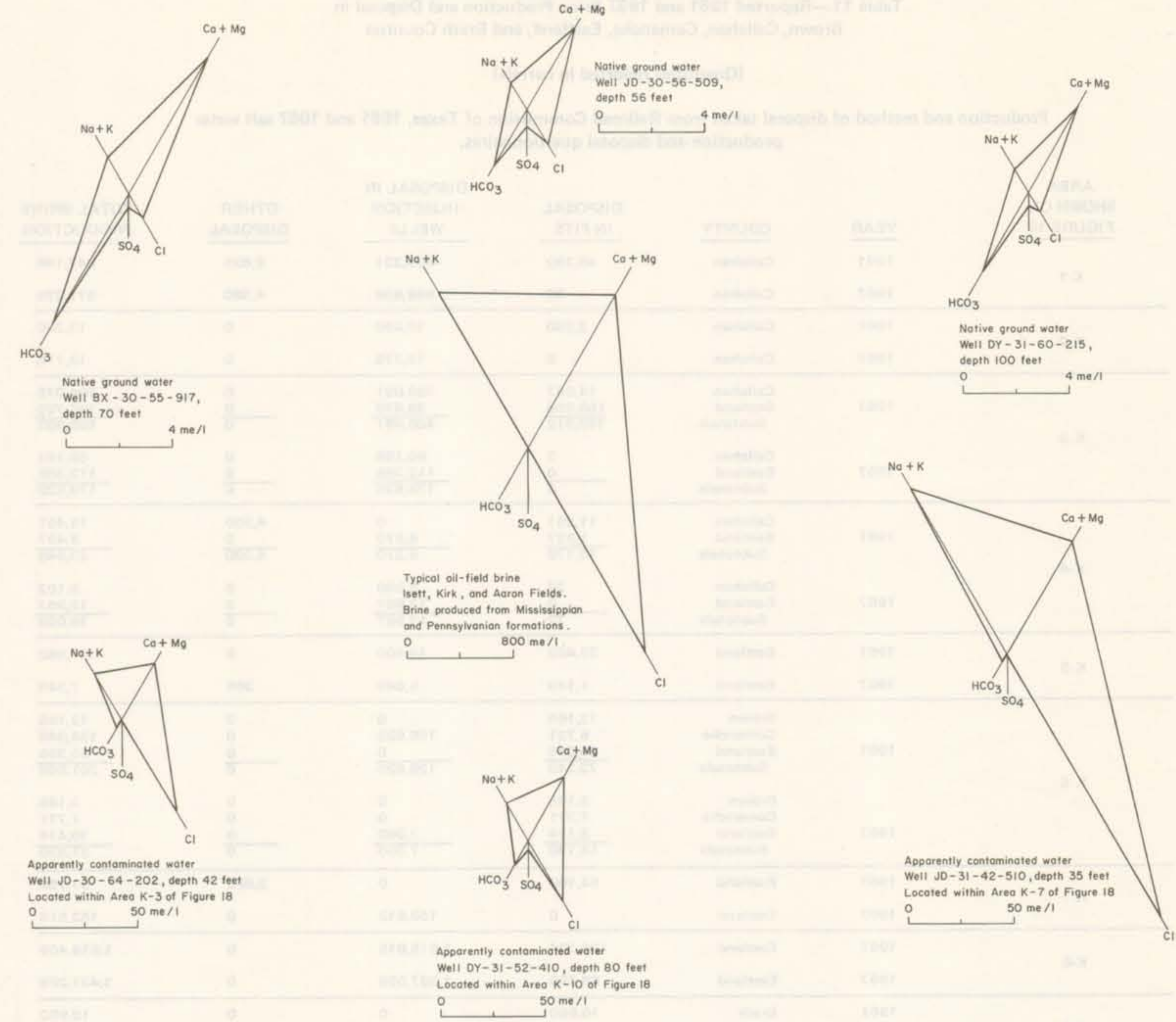

Figure 19

Diagrams of Chemical Analyses of Ground Water and a Typical Oil-Field Brine

and east of the Balcones Fault Zone. The ground water normally occurs under artesian conditions, except in the immediate outcrop area where water-table conditions prevail. The water occurs in fractures and joints, and in solution channels that have been developed and enlarged by the solvent action of the water. These channels and cavities are all sizes, some as large as caves.

The Edwards is recharged by infiltration of rainfall and by seepage from streams that cross the outcrop. Because of the high rate of streamflow seepage into the underlying Edwards, some streams crossing the outcrop flow only during floods. The movement of water in the Edwards is generally in an east-southeast direction. Although the rate of movement is undetermined, it may be relatively fast in local areas because of the large solution channels. The approximate altitude of water levels in wells and the various directional trends of movement are illustrated on Figure 52. Ground water discharges naturally from the Edwards as seeps and springs. The two largest springs in the study region are Barton Springs in the city of Austin, with an average flow of 40 cubic feet per second (cfs), and Salado Springs in Bell County, with an average combined flow of 12 cfs. Artificial discharge occurs when wells are drilled into the Edwards and either pumped or allowed to flow. The Edwards furnishes large quantities of water to public supply and irrigation wells, with yields as high as 2,000 gpm reported.

The hydraulic properties of the Edwards are generally undetermined due to large variations and a lack of sufficient data. The random occurrence of solution channels in limestone aquifers makes it difficult, if not impossible, to determine transmissibilities and permeabilities in any given area.

Water levels in a number of observation wells completed in the Edwards and associated limestones are measured periodically, and these measurements indicate that variations in climatic conditions are the principal factors in the fluctuations of water levels. Locally, heavy pumpage will cause temporary declines in water levels. The altitudes of the water levels in the Edwards and associated limestones, in the spring of 1967, are shown on Figure 52.

The water in the Edwards is usually a calcium bicarbonate type, of good quality except that it is very hard. A gradual deterioration in the quality of the water occurs downdip from the outcrop; the approximate downdip limit of fresh to slightly saline water is shown on Figure 30. The water is generally within the recommended limits for drinking water as established by the U.S. Public Health Service, except near its downdip limit of fresh to slightly saline water where higher concentrations of dissolved minerals occur. In most areas, except in the extreme downdip area, water from the Edwards is suitable for public supply, irrigation, and industrial use. Treatment for hardness may be required prior to use for industrial purposes. Ranges of constituents and properties of water in the aquifer are presented in Table 14.

The Edwards is used extensively as a source of public supply and domestic water. The cities of Round Rock and Georgetown and numerous other smaller communities obtain their water supply from wells completed in the Edwards. Many of the farms and ranches in Bell, Williamson, and Travis Counties, where usable supplies are available, obtain their water from the Edwards. The estimated amount of water used from the Edwards in 1967 was 2,100 acre-feet for public supply, 930 acre-feet for domestic and livestock use, 230 acre-feet for industrial use, and 30 acre-feet for irrigation, giving a total of 3,290 acre-feet. A general lack of sufficient data prohibits an accurate evaluation of the Edwards and associated limestones regarding its potential development. However, the flow of springs and the high yields of some wells indicate that the aquifer is capable of supporting future water development, particularly in southern Bell and central Williamson Counties. A detailed ground-water investigation is needed in order to completely determine the quantity of water available.

Woodbine Group

The Woodbine Group exists as an aquifer only in the extreme northeast corner of the study region, with fresh to slightly saline water occurring only in Hill County. Counties adjoining the study region, where the Woodbine also contains fresh to slightly saline water, are Ellis, Johnson, and Navarro.

Table 12.—Range of Constituents and Properties of Ground Water From Representative Wells in the Glen Rose Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

CONSTITUENT OR PROPERTY	BELL COUNTY	FALLS COUNTY	HAMILTON COUNTY	TRAVIS COUNTY
Silica (SiO_2)	4	96	12	6
Iron (Fe)	.2	.35	—	43.5
Calcium (Ca)	48 - 68	272	38	284
Magnesium (Mg)	26 - 29	56	26	237
Sodium and Potassium (Na + K)	915 - 916	1,332	105	208
Bicarbonate (HCO_3)	464 - 466	201	273	272 - 409
Sulfate (SO_4)	708 - 733	3,206	109	1,680
Chloride (Cl)	770 - 817	217	66	14 - 66
Fluoride (F)	2.1	2	—	3.5
Nitrate (NO_3)	4.7	.4	.2	.4
Boron (B)	—	—	—	—
Dissolved solids	2,730 -2,773	5,281	490	2,664
Total hardness ($CaCO_3$)	239 - 277	909	202	566 -1,690
Percent sodium (percent)	88 - 89	76	53	16
Specific conductance (micromhos at 25°C)	—	—	839	1,040 -2,930
pH	7.3	6.2	7.6	7.1- 7.5
Sodium-adsorption ratio (SAR)	24 - 26	19.2	3.2	1.6

Table 14.—Range of Constituents and Properties of Ground Water from Representative Wells in the Edwards and Associated Limestones

Analyses given are in (milligrams per liter) except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

CONSTITUENT OR PROPERTY	BELL COUNTY	WILLIAMSON COUNTY	TRAVIS COUNTY
Silica (SiO_2)	—	8 - 27	12 - 14
Iron (Fe)	0	0 - 3.4	.22- 7.4
Calcium (Ca)	106	10 - 110	71 -101
Magnesium (Mg)	25	3 - 33	10 - 32
Sodium and Potassium (Na + K)	5	6.7- 650	34 - 46
Bicarbonate (HCO_3)	353	294 - 560	329 -338
Sulfate (SO_4)	16	6.8- 549	33 - 38
Chloride (Cl)	53	10 - 489	30 - 50
Fluoride (F)	1	.1- 8	.5 - .6
Nitrate (NO_3)	19	0 - 36	—
Boron (B)	—	0 - 2.2	—
Dissolved solids	400	310 -1,848	379 -413
Total hardness ($CaCO_3$)	372	37 - 367	247 -314
Percent sodium (percent)	3	4 - 96	19 - 29
Specific conductance (micromhos at 25°C)	—	342 -2,940	735
pH	7.0	6.9- 8.5	7.5
Sodium-adsorption ratio (SAR)	.11	.2- 31	.8 - 1.3

Water occurs in saturated sand beds under both water-table and artesian conditions. Water-table conditions occur in and immediately adjacent to the outcrop while artesian conditions prevail downdip.

Recharge to the Woodbine occurs in its outcrop, which consists of a permeable, sandy soil conducive to infiltration of rainfall and seepage from streams. The movement of water is generally downdip at approximately right angles to the strike of the beds. The direction of movement is eastward with an average hydraulic gradient of 20 feet per mile, with only minor local variations. A small cone of depression at Hillsboro causes water to move into this area from all directions.

Discharge of water from the Woodbine occurs artificially through wells and naturally through springs, seeps, evapotranspiration, and intraformational leakage.

There were no aquifer tests conducted in wells completed in the Woodbine. Coefficients of transmissibility determined from specific capacities ranged from 0 to 4,000 gpd/ft. These specific capacities were obtained from water well drilling contractors. Transmissibilities are low where the sand is thin or shaly, and are higher where the sand is thick and relatively clean and permeable. The areas of sand accumulations are shown on Figure 53, which illustrates the approximate net thickness of sand, excluding shale, containing fresh to slightly saline water in the Woodbine. In areas of the thickest accumulations, the transmissibility will be the highest. Several aquifer tests must be conducted in order to accurately determine the transmissibility and permeability of the Woodbine Group in the study region.

Water levels in a number of observation wells completed in the Woodbine were measured periodically and indicated a seasonal fluctuation, with the lowest water levels occurring in late summer and the highest in early spring. A gradual decline in water levels has occurred in the Woodbine and, based on present and expected future pumpage, the water levels will continue to decline. The rate of decline is undetermined; therefore, a network of observation wells should be established and measured on a regular periodic basis in order to determine the actual rate of decline. The approximate altitude of water levels in wells completed in the Woodbine is illustrated on Figure 54.

The water in the Woodbine is usually a soft, sodium bicarbonate type of fair quality, except in the immediate outcrop area where it is a hard, calcium bicarbonate type of good quality. The water becomes increasingly mineralized downdip, with the largest increases occurring predominantly in sodium, chloride, and sulfate ions. In most parts of the area, the concentrations of sulfate, sodium, chloride, and dissolved solids generally exceed the maximum limits recommended by the U.S. Public Health Service. The water is generally too highly mineralized for industrial or irrigation use. Ranges of constituents and properties of water in the Woodbine Group are presented in Table 15.

The Woodbine is used primarily as a source of water for rural domestic supply and livestock; however, several small towns and industries in Hill County obtain their supply from the Woodbine. Total pumpage from the Woodbine in 1967 was 580 acre-feet. Rural domestic and livestock uses accounted for 350 acre-feet, public supply was 120 acre-feet, and industries used 110 acre-feet. This pumpage is entirely limited to Hill County, since this is the only county in the study region where usable Woodbine water occurs. The area where the most development has occurred is in the vicinity of Hillsboro and north to Itasca. For future development, the area most favorable appears to be the extreme eastern edge of Hill County, where a thick sand section is present, however, the water in this area may be too mineralized for public supply or industrial use.

The amount of water available for development from the Woodbine Group was estimated by using the following assumptions: (1) the effect of pumping is such that the static water level is drawn down to the top of the aquifer, (2) the top of the aquifer is 400 feet below land surface, and (3) the line along the top of the aquifer at this 400-foot depth is roughly parallel to the outcrop.

In determining the quantity of water available, the following were calculated: (1) the total amount of water obtained from storage by lowering the static water level to the top of the

Table 13.—Range of Constituents and Properties of Ground Water From Representative Wells in the Paluxy Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

CONSTITUENT OR PROPERTY	BOSQUE COUNTY	COMANCHE COUNTY	CORYELL COUNTY	ERATH COUNTY	HAMILTON COUNTY	HILL COUNTY	JOHNSON COUNTY	SOMERVELL COUNTY
Silica (SiO_2)	8.4 - 14	7 - 14	8 - 9	14 - 15	8.6- 21	8 - 20	10 - 12	17
Iron (Fe)	.16- 16.8	3.9- 4.9	.92	—	.4- 1.08	.22- .8	.02	—
Calcium (Ca)	2 - 107	10 -100	6 - 44	97 -100	8 - 204	2 - 12	.6 - 1.5	66
Magnesium (Mg)	1 - 31	4 - 29	12 - 35	9 - 9.9	1.4- 78	1 - 5	.4	29
Sodium and Potassium (Na + K)	21 - 450	16 -196	428 - 740	13 - 17	13 - 234	386 - 495	185 - 270	29
Bicarbonate (HCO_3)	281 - 532	332 -378	540 - 640	318 -322	206 - 401	476 - 610	430 - 502	320
Sulfate (SO_4)	0 - 458	35 - 57	336 -1,140	16 - 19	20 - 620	215 - 586	28 - 251	59
Chloride (Cl)	12 - 120	16 - 97	82 - 179	12 - 21	10 - 59	37 - 82	10 - 44	23
Fluoride (F)	.1 - 5.8	.2- .6	6.1 - 8.4	.3- .4	.3- 2.4	3 - 5.8	.5 - 2.2	.4
Nitrate (NO_3)	0 - 6.8	.4- .5	.4	6.5- 16.5	.4- 70	.4 - 5.3	0 - .2	.4
Boron (B)	—	—	—	—	—	—	0 - 1	—
Dissolved solids	311 -1,300	394 -532	1,200 -2,420	339 -342	289 -1,110	959 -1,418	451 - 657	380
Total hardness ($CaCO_3$)	10 - 310	43 -328	64 - 254	282 -288	33 - 830	10 - 51	3 - 14	286
Percent sodium (percent)	14 - 98	10 - 91	86 - 94	9 - 11	8 - 94	95 - 99	99	18
Specific conductance (micromhos at 25°C)	543 -1,950	641 -910	1,820 -3,330	573 -596	488 -1,450	1,580 -2,368	752 -1,700	641
pH	6.8 - 8.4	7.0- 8.3	7.8 - 8.2	6.8- 7.4	6.8- 8.0	8.2 - 8.9	8.3 - 8.6	7.5
Sodium-adsorption ratio (SAR)	.5 - 32	.4- 13	20 - 23	.3- .4	.4- 18	28 - 56	47 - 53	.7

Table 15.—Range of Constituents and Properties of Ground Water From Representative Wells in the Woodbine Group

Analyses given are in (milligrams per liter) except percent sodium, specific conductance, pH, and sodium-adsorption ratio.

Single values appear where only one analysis or value was available.

CONSTITUENT OR PROPERTY	ELLIS COUNTY	JOHNSON COUNTY	NAVARRO COUNTY	HILL COUNTY
Silica (SiO_2)	12 - 14	—	12 - 13	7 - 100
Iron (Fe)	.06- .2	.02	—	.02- 2.5
Calcium (Ca)	1.5 - 4	—	3.5- 5.8	1.5 - 226
Magnesium (Mg)	.9 - 1.6	—	1.6	0 - 16
Sodium and Potassium (Na + K)	356 - 520	—	673 - 849	23 -1,000
Bicarbonate (HCO_3)	590 - 674	—	708 - 924	23 - 850
Sulfate (SO_4)	151 - 516	249	372 - 520	47 - 670
Chloride (Cl)	48 - 79	57	252 - 500	21 - 550
Fluoride (F)	1.4 - 3.2	—	4.6- 4.7	.2 - 4.5
Nitrate (NO_3)	0 - .4	—	.5- 11	.2 - 2.5
Boron (B)	0 - 2.5	—	—	1.5 - 1.7
Dissolved solids	904 -1,680	—	1,830 -2,200	162 -2,662
Total hardness ($CaCO_3$)	7 - 14	264	15 - 21	4 - 690
Percent sodium (percent)	99	—	98 - 99	22 - 99
Specific conductance (micromhos at 25°C)	1,450 -2,475	1,080	2,940 -3,560	255 -4,032
pH	8.1 - 8.3	7.3	7.9- 8.2	5.5 - 8.5
Sodium-adsorption ratio (SAR)	60 - 61	—	64 - 94	1.2 - 73

aquifer where this depth is 400 feet below land surface, and (2) the amount of water that the aquifer will transmit annually, after the static water level has been lowered to 400 feet below the land surface.

The total amount of water available from storage was determined by calculating the volume affected when the static water level is lowered from its 1967 level to a proposed level 400 feet below the land surface. This volume is multiplied by the estimated coefficient of storage and then converted to acre-feet. For the Woodbine Group this amounted to 700 acre-feet. This amount can be pumped from storage only once, not annually, and should not be considered in long-range planning. Using the formula Q = TIW, the amount of water moving through the Woodbine is computed to be approximately 1,836 acre-feet per year. This is the amount that can be pumped annually without lowering the static water level below the top of the aquifer or below 400 feet below land surface. If pumpage exceeds this amount, the water level will decline below the top of the aquifer, and if the pumpage is less than this amount, water will be returned to storage and the water level will rise above the top of the aquifer.

Recharge to the Woodbine appears to be more than adequate to supply the 1,836 acre-feet per year that the aquifer is capable of transmitting. The outcrop of the Woodbine Group within the study region is approximately 86,270 acres. Therefore, less than 0.3 inch of precipitation, or less than 1 percent of the average annual precipitation of 33 inches is needed to supply the 1,836 acre-feet that the aquifer is capable of transmitting. It is apparent that under these conditions the outcrop receives more recharge than can be transmitted, and the excess will be discharged in the outcrop by natural means.

In 1967, approximately 580 acre-feet of ground water was pumped from the Woodbine; therefore, under the above assumed conditions an additional 1,256 acre-feet can be pumped annually without lowering the static water level below the top of the aquifer.

Water levels will continue to decline as pumpage increases. However, with proper well spacing, declines should not be severe. Only in areas of concentrated pumpage will severe water-level declines be experienced.

A detailed investigation of the Woodbine Group is needed in order to fully evaluate the amount and quality of water available.

WELL CONSTRUCTION

Well construction in the study region is generally based on water requirements and economics. Some of the well designs used to produce from the sand and gravel aquifers in the region are illustrated on Figure 20.

Irrigation wells producing from the Antlers and Travis Peak Formations in Comanche, Eastland, Erath, and adjacent counties are generally of high capacity (30 to 500 gpm), straight walled, cased, and gravel packed from the surface to total depth. The casing is torch slotted opposite the desired water-bearing unit. The casing most commonly used is about 8 5/8 inches in diameter, however, sizes ranging from 5 to 18 inches in diameter may be used.

Most public supply and industrial wells in the region are completed in the Hensell or Hosston Members of the Travis Peak Formation. In Comanche, Eastland, Erath, and adjacent counties, these wells are completed in the Antlers or both sand members of the Travis Peak (dual completion). Generally these wells are straight walled and cased, and may be cemented from the surface to the top of the desired water-bearing unit. The casing is torch or mill slotted opposite the water-producing interval. Many of the high capacity wells are underreamed, gravel packed, and completed with selective screens opposite the chosen water-bearing unit. Some of the rural water-supply corporations cement from top to bottom and gun perforate the casing opposite the water-producing zones. Sometimes the casing may only extend to the top of the water-bearing unit with an "open hole" below. Surface casing in most public supply and industrial wells is cemented in place to restrict seepage of surface water down the well bore, and may be as large as 22 inches in diameter. The blank liner (casing) used in public supply and industrial wells generally ranges from 3 to over 13 inches in diameter.

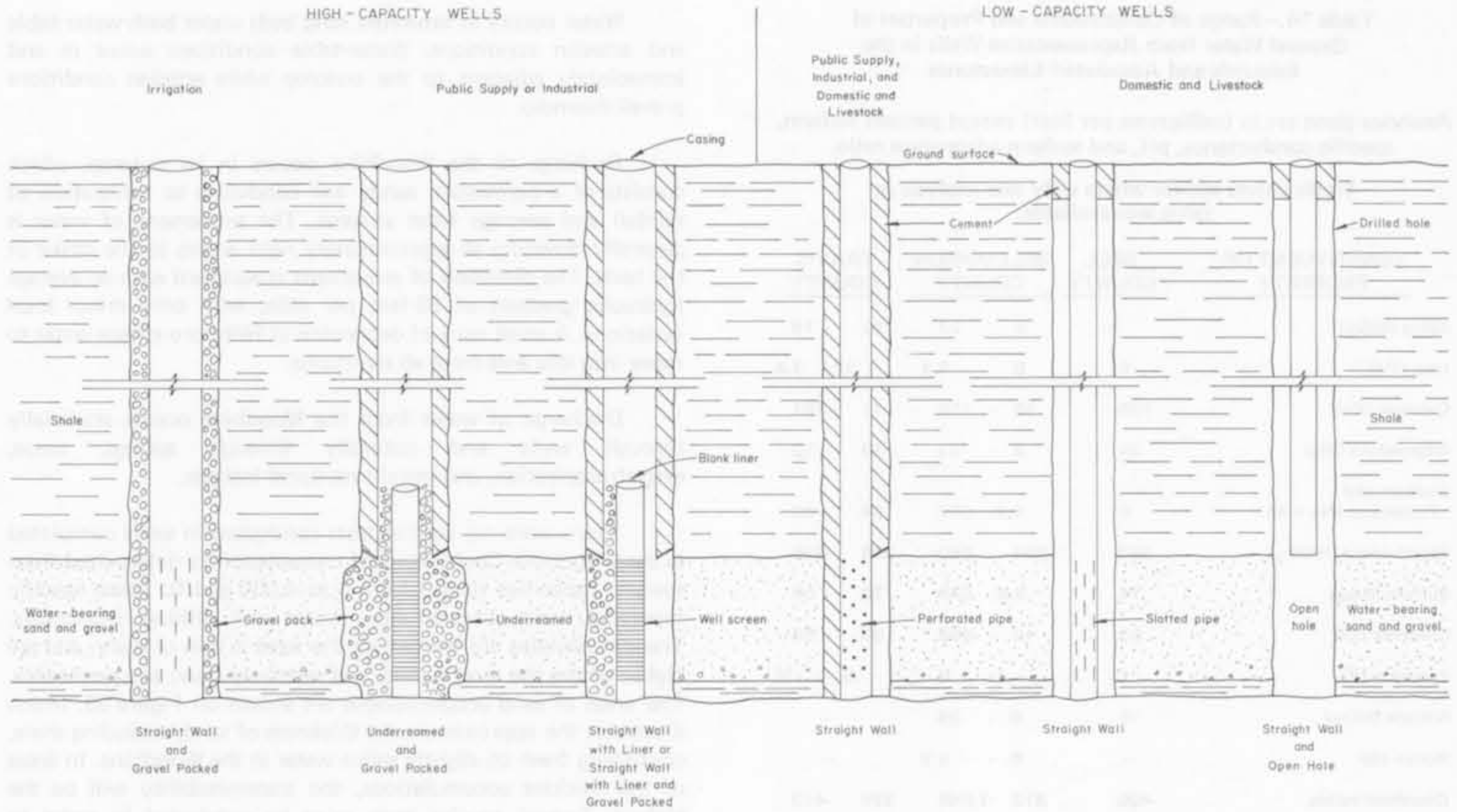

Figure 20
Diagrams of Well Construction Used to Produce Water From Sand and Gravel Aquifers in the Study Region

Domestic wells throughout the region are generally straight walled and either cased from the surface to the top of the desired water-bearing unit and left as an "open hole" below, or cased from the surface to the total depth and mill or torch slotted opposite the desired water-bearing unit. Cementation is restricted to a surface platform and a collar around the casing, extending down approximately 10 feet. Casing used in domestic wells generally ranges from 3 to over 12 inches in diameter.

GROUND-WATER PROBLEMS

Improper Well Construction

Improper well construction in the region can be attributed to one or all of the following: (1) insufficient casing, (2) open-hole completions, (3) slotting or perforating, (4) improper gravel packing, (5) insufficient cementation, and (6) lack of screened completions.

Wells having insufficient casing or no casing at all may permit the borehole to collapse at any point or sand-up at the water-producing interval. In any case the life of the well is reduced and, should the borehole collapse, the pump may become damaged or trapped below. In addition, the possibility of contamination from other undesirable water zones is increased.

Open-hole completion, although reducing the initial cost of well construction, increases the likelihood of sanding-up or caving by the water-bearing unit and thus reduces the life of the well. If caving occurs, the possibility of contamination from upper zones of undesirable water is increased.

The methods most commonly used to complete fully cased wells in the region are slotting (mill or torch) or perforating. These methods, although acceptable, are not the most effective over a long period of time because they permit sand to enter and ultimately reduce the life of the well. If sufficient sand enters, yields are reduced, and the pump may be damaged or lost by being sanded in place. In any case, pumping and maintenance costs are increased. This sanding problem is very common in irrigation wells producing from the Travis Peak Formation in Comanche, Eastland, Erath, and adjacent counties.

Gravel packing, although an important step in proper well completion, has not been very effective in the northwest outcrop area of the Antlers and Travis Peak Formations, because the proper procedure has not been followed. Most irrigation wells in this area are gravel packed by hand shoveling the gravel-pack material between the well casing and borehole. This method allows separation of the material into its various component sizes and bridging between the borehole and casing. Proper gravel packing should be preceded by a sieve analysis of the prospective water-bearing unit to determine the proper size material to use. In the northwest outcrop area, material selected for gravel packing is based on availability and not on sieve analyses of the water-bearing sands. Improper gravel-packing procedures allows sand to enter the well, resulting in reduced yields, increased operating costs, and an ultimate reduction in the life of the well.

Proper cementation of the casing to the borehole is an important step in correct water-well construction. This is especially true in areas where bad quality water may exist above or below a usable water interval. Without cementation, the undesirable water is allowed to travel up or down in the space between the casing and borehole and contaminate the usable water. Many of the early water wells and most of the domestic and livestock wells drilled in the study region have little or no cementation and therefore are susceptible to contamination from undesirable water zones.

Because of the high initial cost, most wells in the region are not equipped with screens. If screens were used, the yield and life of the well would be increased and the long-term maintenance cost reduced.

The following are recommendations for proper well construction and completion in the study region. Wells should be drilled to the base of the aquifer in order to utilize its maximum saturated thickness, thus resulting in a higher specific capacity, reducing drawdowns, and permitting greater yields. In wells that use turbine pumps, the hole must be deep enough and straight enough to permit satisfactory operation of the pump. All wells should be cased from surface to total depth. Casing used should be large enough (diameter), extend down far enough to accomodate a pump capable of producing the required quantity of water, and allow for the pump to be lowered to keep up with expected water-level declines. In addition, the casing should be selected for its ability to resist corrosion, deterioration, and collapse. Gravel packing, when used, should be preceded by a sieve analysis of the water-bearing unit to properly determine the size of the material that should be used. Sufficient gravel should be used to completely and uniformly pack the casing, thus reducing sand production. Well-development tests should be continued as long as necessary, at a reduced pumping rate, to insure maximum production with minimum drawdown. Maximum pumping (over-pumping) during a well-development test, although generally practiced, many leave some of the sand grains bridged, thus only partially stabilizing the aquifer. Over-pumping seldom brings about best results or full stabilization of the aquifer. Whenever economically possible, the well should be completed with a properly designed well screen that allows water to flow freely into the well, prevents sand from entering with the water, and serves as a structural retainer to support the borehole. The screened water well calls for an additional investment which will, in the long run, produce maximum efficiency and economy by increasing the well yield and reducing maintenance costs. The screened interval should be below the anticipated pumping level.

Rapid Decline of Water Levels

A serious problem associated with the development of ground water from the Travis Peak Formation in the study region is the decline of artesian pressure (water level) in areas of large ground-water withdrawals. The area most seriously affected is along and adjacent to Interstate Highway 35 from Temple, through Waco, and north to Hillsboro. The concentration of public supply and industrial wells in this area, the high rate of continuous ground-water withdrawal, and the relatively low permeability of the sands have caused rapid and large water-level declines.

As a result of water-level declines in this area, pumps must be set deeper and larger motors must be installed. The higher pumping lifts cause increased operating expenses. In addition, new wells are being drilled to help meet increased demands, causing increased water-level declines. These new wells have deep original pump settings and large motors to help offset the expected water-level declines.

The total accumulated water-level decline in the Travis Peak Formation for the period 1900 to 1967 is illustrated on Figure 42. The projected declines from 1967 to 1975 for the Hensell and Hosston Members are illustrated on Figures 43 and 46. Additional projected water-level declines in the Hensell and Hosston Members for the period 1967-1990 are shown on Figures 44 and 47, and for the period 1967-2020 on Figures 45 and 48.

Contamination of Ground Water

Contamination of the native ground water is a serious problem in some areas within the study region. Most of the reported contamination areas are located in the northwestern part of the study region where the Travis Peak Formation crops out. These areas are illustrated on Figures 18 and 35.

Most of the contamination reported in the northwestern area is by salt water from oil-field brines. These brines have caused vegetation kills where they have been allowed to run out on the ground surface. In areas where the brines have percolated downward, they have contaminated the native ground water, resulting in higher concentrations of dissolved minerals. Several irrigation wells and test wells drilled for irrigation purposes have been abandoned because of the excessive total dissolved solids in the water.

Occasionally in areas of unplugged or improperly plugged oil or gas wells, the oil or natural gas has entered fresh-water sands. When a water well is drilled and pumped, the oil or natural gas can enter the well along with the water and become a fire hazard and a hazard to crops and livestock. In some of the irrigation wells that were located near abandoned, unplugged oil tests, the quality of the ground water has improved after the oil tests were reentered and properly plugged.

Deterioration of the quality of native ground water may also occur by pollution from organic matter, commonly sewage, which may result in bacterial contamination and high concentrations of nitrate. Concentrations of nitrate in excess of 45 mg/l have been known to cause infant cyanosis (methemoglobinemia or "blue baby" disease). This generally occurs in shallow wells, uncased or improperly cased, in which surface water can enter. Properly casing and cementing wells will help prevent this type of contamination.

The Glen Rose Formation is known to contain highly mineralized water in some areas and is a possible source of contamination to the underlying Travis Peak Formation, particularly when wells penetrating the Glen Rose are not properly cased and the highly mineralized water is allowed to intermingle with the good water of the Travis Peak. This condition does exist in the region and usually affects domestic and livestock wells that have little or no casing.

There is possible natural contamination also in the Balcones Fault Zone. This contamination is generally the result of intermingling along faults of saline water from overlying and underlying formations with good quality native water of the Travis Peak Formation. This type of contamination is usually limited to the immediate vicinity of the fault. However, due in part to the numerous faults in the Balcones Fault Zone, a general deterioration in the chemical quality of water in the Travis Peak Formation east of the fault zone is apparent.

CONCLUSIONS

The Antlers and Travis Peak Formations are important water-bearing units that furnish water of usable quality in essentially the entire study region. The Antlers is an important aquifer in Brown, Callahan, Comanche, and Eastland Counties, and is hydrologically connected to the Travis Peak in Brown, Comanche, and Eastland Counties. The Travis Peak is present as a water-bearing unit in most of the region and contains the Hensell and Hosston Members which are the two most important aquifers.

Downdip the supply of usable quality ground water in the Travis Peak Formation is large; however, in areas of heavy pumpage, the amount of ground water being withdrawn exceeds the natural recharge. This heavy pumpage has created large water-level declines in Belton, Gatesville, Hillsboro, Itasca, McGregor, and Waco. Any additional development in these areas will only increase the declines.

The computer aquifer simulation study of the Travis Peak Formation in the downdip areas indicates that tremendous water-level declines should occur downdip in the existing areas of heavy pumpage as a result of projected pumpage; pumpage should be reduced in the overdeveloped areas in order for water levels not to fall below the 400- to 500-foot interval below land surface or the top of the water-bearing sands; and additional ground-water supplies, in excess of the 1966 downdip pumpage, can be economically developed by restricting pumpage in the overdeveloped areas and increasing pumpage in the areas most favorable for development. About 40,000 acre-feet of ground water can be pumped annually from the Travis Peak downdip from its outcrop in the study region until the year 2020. This proposed annual pumpage represents an approximate increase of 23,248 acre-feet of water over the 1966 municipal, industrial, and irrigation use for this area.

Additional quantities of ground water can be developed from the Antlers and Travis Peak Formations in the outcrop areas outside the calcareous facies. Approximately 87,150 acre-feet is recharged annually to the Antlers and Travis Peak in this area. In 1966, only 6,715 acre-feet of ground water from this outcrop area was used for irrigation, public supply, and industrial purposes; the remainder of the available water was lost by natural rejection or was transmitted downdip to the Hensell and Hosston aquifers. Allowing for full development in the downdip areas (40,000 acre-feet annually) and the 6,715 acre-feet utilized in 1966, it appears an additional 40,000 acre-feet can be pumped annually in the outcrop area under optimum conditions without affecting the downdip availability of ground water from the Travis Peak Formation.

Contamination of native ground water within the Antlers and Travis Peak Formations by oil-field brines is a serious problem in Brown, Callahan, Comanche, Eastland, and Erath Counties. Contamination has occurred through the use of unlined disposal pits and from unplugged or improperly plugged oil or gas wells. This ground water may remain contaminated for many years after the source of contamination has been removed, and may migrate downdip and affect areas that presently contain good native ground water.

Water of good quality is available from the Glen Rose and Paluxy Formations, Edwards and associated limestones, and the Woodbine Group in parts of the study region. Approximately 1,836 acre-feet of ground water is available from the Woodbine Group and approximately 930 acre-feet is available from the Paluxy Formation. These amounts can be pumped annually without lowering the static water levels below the top of the aquifers or below 400 feet below land surface.

RECOMMENDATIONS

The water levels in 407 observation wells that are completed in the Antlers and Travis Peak Formations and the other principal Cretaceous aquifers are measured to determine seasonal and long-term changes. Seasonal variations were determined by the monthly measurement of 68 wells from September 1966 to February 1968. In May 1964, well ST-40-31-802 in McLennan County was equipped with a recorder that continuously measured water-level changes. This water-level program should be continued and expanded in order to determine the effects of present and future pumpage. Additional observation wells should be properly spaced throughout the region with emphasis placed on the areas of heavy pumpage.

A program should be established to periodically sample ground water for chemical analyses to detect possible changes in water quality. The collection of water samples at regular intervals will provide information with regard to movement of oil-field brine contaminated ground water in the outcrop areas, and changes of chemical quality in areas of heavy pumpage.

The periodic collection of water-use information should be continued and expanded in order to improve the quality of data received. This program should include collection of data on (1) municipal and industrial pumpage, (2) power consumption by ground-water irrigators, and (3) power and yield tests on certain irrigation wells in the study region. Additional power and yield tests are needed to more accurately relate amounts of the electric power used to gallons of ground water produced.

Additional pumping tests should be conducted on wells completed in the Cretaceous aquifers. This program is needed to accurately determine the aquifer characteristics of the Travis Peak Formation in the Balcones Fault Zone, the northwest outcrop area, and the calcareous facies; and to obtain accurate aquifer characteristics of the other principal Cretaceous aquifers.

Recharge studies should be initiated in the outcrop areas of the Antlers and Travis Peak Formations. The relationship between rainfall and recharge should be accurately determined.

In the digital computer simulation of the Hensell and Hosston aquifers, the projected values of water-level drawdowns were based on assumptions of pumpage, recharge, and to some extent, aquifer coefficients. In 1975, the model's water-level drawdown prediction for this period should be compared with the data obtained from the continuing measurement programs. This will establish the model's accuracy and provide a basis for any needed adjustments. After the model's accuracy has been verified and adjustments made, the device should be a reliable tool for water-resource planning in the study region.

Developing and utilizing ground water for maximum efficiency requires adequate planning. Future development should be based on a program of test drilling, test pumping, and chemical analyses of water from the various producing sands. Such preliminary data can be used to determine the most efficient well completion method, optimum pumping rate, efficient pump setting, proper well spacing, and feasibility of drilling additional wells. Large concentrated withdrawals of ground water in small areas should be avoided.

Irrigators in Comanche, Eastland, and Erath Counties should consider the use of screens in future well construction and completion. The properly screened water well requires an additional investment which will, in the long run, produce maximum efficiency and economy by increasing the well yield and reducing maintenance costs.

SELECTED REFERENCES

Adkins, W. S., 1923, Geology and mineral resources of McLennan County, Texas: Univ. Texas Bull. 2340, 202 p.

Adkins, W. S., and Arick, M. B., 1930, Geology of Bell County Texas: Univ. Texas Bull. 3016, 92 p.

Adkins, W. S., and Lozo, F. E., 1951, Stratigraphy of the Woodbine and Eagle Ford, Waco area, *in* The Woodbine and adjacent strata of the Waco area of central Texas: Southern Meth. Univ., Fondren Sci. Ser. 4, p. 105-165.

American Geological Institute, 1957, Glossary of geology and related sciences: Am. Geol. Inst., 396 p.

American Water Works Association, 1950, Water quality and treatment: Am. Water Works Assoc. Manual, 2d. ed., tables 3-4, p. 66-67.

Arnow, Ted, 1957, Records of wells in Travis County, Texas: Texas Board Water Engineers Bull. 5708, 29 p.

Atlee, W. A., 1962, The lower Cretaceous Paluxy Sand in central Texas, *in* Baylor Geological Studies: Baylor Univ. Bull. 2, 25 p.

BJ Service, Inc., 1960, The chemical analyses of brines from some fields in North and West Texas: Unpublished rept.

Bennett, R. R., 1941, Ground water in the vicinity of Killeen, Texas: U.S. Geol. Survey open-file rept., 10 p.

_____1942, Memorandum on ground water in the area about 8 miles north of Belton, Texas: U.S. Geol. Survey open-file rept., 5 p.

Boone, P. A., 1968, Stratigraphy of the Basal Trinity (lower Cretaceous) Sands of central Texas, *in* Baylor Geological Studies: Baylor Univ. Bull. 15, 64 p.

Broadhurst, W. L., 1943, Results of pumping tests of a well (Ed. Huess No. 1) 3.7 miles northeast of Killeen, Bell County, Texas: U.S. Geol. Survey open-file rept., 8 p.

Bruin, J., and Hudson, H. E., Jr., 1961, Selected method for pumping test analysis: Illinois State Water Survey Rept. 25, 54 p.

Bryan, F., 1951, The Grand Prairies of Texas, *in* The Woodbine and adjacent strata of the Waco area of central Texas: Southern Meth. Univ., Fondren Sci. Ser. 4, p. 1-11.

California State Water Pollution Control Board, 1952, Water quality criteria (including addendum no. 1, 1954): California State Water Pollution Control Board Pub. 3, 676 p.

Carr, J. T., Jr., 1967, The climate and physiography of Texas: Texas Water Devel. Board Rept. 53, 27 p.

Clark, W. I., 1937, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Milam County, Texas: Texas Board Water Engineers duplicated rept., 57 p.

Cooper, H. H., Jr., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: Am. Geophys. Union Trans., v. 27, no. 4, p. 526-534.

Cronin, J. G., Follett, C. R., Shafer, G. H., and Rettman, P. L., 1963, Reconnaissance investigation of the ground-water resources of the Brazos River basin, Texas: Texas Water Comm. Bull. 6310, 152 p.

Cumley, J. C., Cromack, G. H., and Follett, C. R., 1942, Records of wells and springs, drillers' logs, chemical analyses, and map showing location of wells and springs in Williamson County, Texas: Texas Board Water Engineers duplicated rept., 93 p.

Dallas Morning News, 1967, Texas almanac and state industrial guide, 1968-1969: A. H. Belo Corporation, 736 p.

Darton, N. H., Stephenson, L. W., and Gardner, Julia, 1937, Geologic map of Texas: U.S. Geol. Survey map.

Davis, D. A., 1938, Records of wells, drillers' logs, water analyses, and map showing location of wells in Brown County, Texas: Texas Board Water Engineers duplicated rept., 25 p.

Dean, H. T., Arnold, F. A., and Elvove, Elias, 1942, Domestic water and dental caries: U.S. Public Health Service Public Health Repts., v 57, p. 1155-1179.

Dean, H. T., Dixon, R. M., and Cohen, Chester, 1935, Mottled enamel in Texas: U.S. Public Health Service Public Health Repts., v. 50, p. 424-442.

Doll, W. L., Meyer, G., and Archer, R. J., 1963, Water resources of West Virginia: West Virginia Dept. of Nat. Resources, Div. of Water Resources, 134 p.

Fiedler, A. G., 1934, Artesian water in Somervell County, Texas: U.S. Geol. Survey Water-Supply Paper 660, 86 p.

Fisher, W. L., and Rodda, P. U., 1966, Nomenclature revision of basal Cretaceous rocks between the Colorado and Red Rivers, Texas: Bur. of Econ. Geology Rept. of Inv. 58, 20 p.

_____1967, Lower Cretaceous sands of Texas, stratigraphy and resources: Bur. of Econ. Geology, Rept. of Inv. 59, 116 p.

Follett, C. R., 1956, Records of water-level measurements in Hays, Travis, and Williamson Counties, Texas, 1937 to May 1956: Texas Board Water Engineers Bull. 5612, 74 p.

George, W. O., and Barnes, B. A., 1945a, Results of tests on wells at Waco, Texas: U.S. Geol. Survey open-file rept., 15 p.

_____1945b, Results of tests on wells at Waco, Texas: Texas Board Water Engineers duplicated report, 22 p., [1952].

George, W. O., Cumley, J. C., and Follett, C. R., 1941, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs in Travis County, Texas: Texas Board Water Engineers duplicated rept.

George, W. O., and White, W. N., 1942, Ground water in the vicinity of Burnet and Bertram, Burnet County, Texas: U.S. Geol. Survey open-file rept., 12 p.

Guyton, W. F., and George, W. O., 1943, Results of pumping tests of wells at Camp Hood, Texas: U.S. Geol. Survey open-file rept., 24 p.

Guyton, W. F., and Rose, N. A., 1945, Quantitative studies of some artesian aquifers in Texas: Econ. Geology, v. 40, no. 3, p. 193-226.

Hayward, O. T., and Brown, L. F., Jr., 1967, Comanchean (Cretaceous) rocks of central Texas: Soc. of Econ. Paleontologists and Mineralogists, the Permian Basin section, Pub. 67-8, p. 31-48.

Heller, V. G., 1933, The effect of saline and alkaline waters on domestic animals: Oklahoma Agr. and Mech. Coll. Expt. Sta. Bull. 217, 23 p.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 269 p.

Henningsen, R. E., 1962, Water diagenesis in lower Cretaceous Trinity aquifers of central Texas *in* Baylor Geological Studies: Baylor Univ. Bull. 3, 38 p.

Hill, R. T., 1901, Geography and geology of the Black and Grand Prairies, Texas: U.S. Geol. Survey 21st Ann. Rept., pt. 7, 666 p.

Hill, R. T., and Vaughan, T. W., 1902, Description of the Austin quadrangle: U.S. Geological Survey, Geol. Atlas, Folio 76.

Holloway, H. D., 1961, The lower Cretaceous Trinity aquifers, McLennan County, Texas, *in* Baylor Geological Studies: Baylor Univ. Bull. 1, 31 p.

Hull, A. M., 1951, Geology of Whitney Reservoir area, Brazos River, Bosque-Hill Counties, Texas, *in* The Woodbine and adjacent strata of the Waco area of central Texas: Southern Meth. Univ., Fondren Sci. Ser. 4, p. 45-65.

Imlay, R. W., 1944, Correlation of lower Cretaceous formations of the Coastal Plain of Texas, Louisiana, and Arkansas: U.S. Geol. Survey, Oil and Gas Inv. Prelim. chart no. 3.

_____1945, Subsurface lower Cretaceous formations of South Texas: Am. Assoc. Petroleum Geologists Bull., v. 29, no. 10, p. 1416-1469.

Kane, J. W., 1967, Monthly reservoir evaporation rates for Texas, 1940 through 1965: Texas Water Devel. Board Rept. 64, 111 p.

Laxon, Rowland, and others, 1960, Resistivities and chemical analyses of formation waters from the west central Texas area: West Central Texas Section, Soc. Petroleum Engineers of Am. Inst. Mining, Metall., and Petroleum Engineers.

Livingston, Penn, and Bennett, R. R., 1942, Ground water in the vicinity of McGregor, McLennan County, Texas: U.S. Geol. Survey open-file rept., 11 p.

Livingston, Penn, and Hastings, W. W., 1942, Test well at proposed army camp 5 miles southeast of Gatesville, Texas: U.S. Geol. Survey open-file rept., 19 p.

Lohr, E. W., and Love, S. K., 1954, The industrial utility of public water supplies in the United States, 1952, pt. 2: U.S. Geol. Survey Water-Supply Paper 1300, 462 p.

Lozo, F. E., 1951, Stratigraphic notes on the Meness (Comanche Cretaceous) shales, *in* The Woodbine and adjacent strata of the Waco area of central Texas: Southern Meth. Univ., Fondren Sci. Ser. 4, p. 65-93.

Lozo, F. E., and Stricklin, F. L., Jr., 1956, Stratigraphic notes on the outcrop basal Cretaceous, central Texas: Trans. Gulf Coast Assoc. Geol. Soc., v. 6, p. 67-78.

Maier, F. J., 1950, Fluoridation of public water supplies: Am. Water Works Assoc. Jour., v. 42, pt. 1, p. 1120-1132.

Maxcy, K. F., 1950, Report on the relation of nitrate concentration in well waters to the occurrence of methemoglobinema in infants: Natl. Research Council Bull. Sanitary Engineering and Environment, App. D, p. 265-271.

McBride, W. J., 1953, The surface geology of Hamilton County, Texas: Univ. Houston thesis.

Meinzer, O. E., 1923a, The occurrence of ground water in the United States, with a discussion of principles: U.S. Geol. Survey Water-Supply Paper 489, 321 p.

_____1923b, Outline of ground-water hydrology, with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Moore, E. W., 1940, Progress report of the committee on quality tolerances of water for industrial uses: New England Water Works Assoc. Jour., v. 54, p. 263.

Mount, J. R., 1962, Ground-water conditions in the vicinity of Burnet, Texas: Texas Water Comm. Memo. Rept. 62-01, 52 p.

_____1963, Ground-water availability at Whitney, Hill County, Texas: Texas Water Comm. Rept. LD-0263-MR, 15 p.

Mount, J. R. Rayner, F. A., Shamburger, V. M., Jr., Peckham, R. C., and Osborne, F. L., Jr., 1967, Reconnaissance investigation of the ground-water resources of the Colorado River basin, Texas: Texas Water Devel. Board Rept. 51, 107 p.

Mueller, C. B., 1940, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs in Callahan County, Texas: Texas Board Water Engineers duplicated rept., 42 p.

Peckham, R. C., Souders, V. L., Dillard, J. W., and Baker, B. B., 1963, Reconnaissance investigation of the ground-water resources of the Trinity River basin, Texas: Texas Water Comm. Bull. 6309, 110 p.

Price, J. C., 1951, The south Bosque oil field, *in* The Woodbine and adjacent strata of the Waco area of central Texas: Southern Meth. Univ., Fondren Sci. Ser. 4, p. 24-28.

Rayner, F. A., 1959, Records of water-level measurements in Bell, McLennan, and Somervell Counties, Texas, 1930 through 1957: Texas Board Water Engineers Bull. 5902, 29 p.

Rodda, P. U., Fisher, W. L., Payne, W. R., and Schofield, D. A., 1966, Limestone and dolomite resources, lower Cretaceous rocks, Texas: Bur. of Econ. Geology Rept. of Inv. 56, 286 p.

Rodgers, R. W., 1967, Stratigraphy of Glen Rose Limestone, Texas: Soc. of Econ. Paleontologists and Mineralogists, the Permian Basin section, Pub. 67-8, p. 119-130.

Rose, N. A., 1943, Results of pumping tests of wells at tank destroyer center, north Camp Hood near Gatesville, Texas: U.S. Geol. Survey open-file rept., 27 p.

Rose, N. A., and George, W. O., 1942, Ground-water resources in selected areas in Erath, Hood, and Hamilton Counties, Texas: U.S. Geol. Survey open-file rept., 10 p.

Samuell, J. H., 1937, Records of wells, drillers' logs, water-level measurements, analyses of water from wells, streams, and lakes, and map showing locations in Eastland County, Texas: Texas Board Water Engineers duplicated rept., 58 p.

Scofield, C. S., 1936, The salinity of irrigation water: Smithsonian Inst. Ann. Rept., 1934-35, p. 275-287.

Sellards, E. H., Adkins, W. S., and Plummer, F. B., 1932, The geology of Texas, v. I, Stratigraphy: Univ. Texas Bull. 3232, Bur. Econ. Geology, 1007 p., [1933].

Sellards, E. H., and Baker, C. L., 1934, The geology of Texas, v. II, Structural and economic geology: Univ. Texas Bull. 3401, Bur. Econ. Geology, 884 p.

Sundstrom, R. W., and Barnes, B. A., 1942, Ground-water resources in the vicinity of Gatesville, Texas: U.S. Geol. Survey open-file rept., 11 p.

Sundstrom, R. W., Broadhurst, W. L., and Dwyer, B. C., 1949, Public water supplies in central and north-central Texas: U.S. Geol. Survey Water-Supply Paper 1069, 128 p.

Sundstrom, R. W., Hastings, W. W., and Broadhurst, W. L., 1948, Public water supplies in eastern Texas: U.S. Geol. Survey Water-Supply Paper 1047, 285 p.

Texas Water Commission and Texas Water Pollution Control Board, 1963, A statistical analysis of data on oil field brine production and disposal in Texas for the year 1961 *from* an inventory conducted by the Texas Railroad Commission: Railroad Comm. Dist. 3, v. I, 327 p.

Thompson, D. R., 1967, Occurrence and quality of ground water in Brown County, Texas: Texas Water Devel. Board Rept. 46, 143 p.

Thompson, G. L., 1967, Ground-water resources of Ellis County, Texas: Texas Water Devel. Board Rept. 62, 128 p.

Thompson, G. L., 1969, Ground-water resources of Johnson County, Texas: Texas Water Devel. Board Rept. 94, 84 p.

U.S. Public Health Service, 1962, Public Health Service drinking water standards: Public Health Service Pub. 956, 61 p.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Dept. Agr. Handb. 60, 160 p.

Walton, W. C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Rept. 49, 81 p.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods, *with a section on* Direct laboratory methods and bibliography on permeability and laminar flow, by V. C. Fishel: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

Whitney, F. L., 1959, Spicewood quadrangle; manuscript geologic quadrangle map on open-file status, edited by Keith Young: Univ. of Texas, Bur. Econ. Geology map.

Wilcox, L. V., 1955, Classification and use of irrigation waters: U.S. Dept. Agr. Circ. 969, 19 p.

Winslow, A. G., and Kister, L. R., Jr., 1956, Saline-water resources of Texas: U.S. Geol. Survey Water-Supply Paper 1365, 105 p.

Winton, W. M., and Scott, Gayle, 1922, The geology of Johnson County, Texas: Univ. Texas Bull. 2229, 68 p.

Young, Keith, 1967, Comanche Series (Cretaceous), south central Texas: Soc. of Econ. Paleontologists and Mineralogists, the Permian Basin section, Pub. 67-8, p. 9-29.