Geology and Ground-Water Resources of Uvalde County, Texas

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1584

Prepared in cooperation with the Texas Board of Water Engineers and the City of San Antonio

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By F. A. WELDER *and* R. D. REEVES

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By F. A. Welder and R. D. Reeves

ABSTRACT

The principal aquifer in Uvalde County is the Edwards and associated limestones of Cretaceous age. The aquifer underlies an extensive area in south-central Texas extending along the Balcones fault zone from Kinney County eastward to San Antonio, and thence northeastward to Hays County. The hydrologic unit making up the Edwards and associated limestones consists of the Comanche Peak limestone, the Edwards limestone, the Kiamichi formation, and the Georgetown limestone. Other less important aquifers in Uvalde County include the Glen Rose limestone, the Buda limestone, the Austin chalk, and the Leona formation.

Uvalde County occupies parts of two physiographic provinces, the Edwards Plateau on the north and the Coastal Plain on the south; the two provinces are separated by the Balcones fault zone. In the Edwards Plateau the formations of the Edwards and associated limestones crop out on the plateau surface; in the Coastal Plain where the formations have been down-faulted, they underlie younger rocks. In both provinces the formations dip gently toward the south and southeast; the dips are greatest in the Coastal Plain. Igneous intrusions have penetrated the formations in many places in the Coastal Plain, and locally have formed barriers to ground-water movement.

The aquifers in Uvalde County are recharged by precipitation within the county and in the drainage areas of streams entering the county from the north and west. In the Edwards Plateau, the Edwards and associated limestones are recharged by precipitation that falls on the outcrop. The aquifer is drained by springs at the contact with the underlying Glen Rose limestone where streams have cut through the Edwards at the edge of the plateau. These springs maintain the base flow of the streams that drain the plateau. Most of the base flow and much of flood flow of the streams is lost to the Edwards and associated limestones where they crop out in streambeds in the Balcones fault zone. This stream loss to the aquifer constitutes the greatest part of the recharge in the county, although some of the recharge from the West Nueces River enters the county as underflow from Kinney County. The normal annual recharge to the Edwards in Uvalde County is estimated to be about 200,000 acre-feet.

Discharge from the Edwards and associated limestones in Uvalde County can be divided into two major segments: discharge by underflow from the county to the east and south and discharge to the surface through wells and springs. Discharge by underflow during the period 1934–47, when changes in storage were small, is estimated to have been about 190,000 acre-feet per year. During the

drought years 1947–56 the underflow was somewhat less. The discharge to the surface during 1934–47 averaged about 17,000 acre-feet per year. During the 1947–56 drought the rate of discharge to the surface increased principally because of increased use of water for irrigation, reaching a maximum of 58,000 acre-feet in 1956.

The chemical quality of the ground water in Uvalde County ranges between wide limits. Except in the extreme southern part of the county where the water is saline, the water in the Edwards and associated limestones is of good chemical quality except that it is hard. The water in the Glen Rose limestone is saline in many places; the principal objectionable constituents are high concentrations of calcium and magnesium sulfate. The water in the Leona formation is generally of good chemical quality. The water from the other formations varies widely in quality from place to place and no generalizations can be made.

Ground-water withdrawals from the Edwards and associated limestones in Uvalde County probably could be maintained indefinitely at a rate of about 200,000 acre-feet per year, provided that withdrawals north and west of the county were not increased. However, continued withdrawals at this rate would cause wells in structurally high areas to go dry, and underflow into Medina County would cease. Furthermore, saline water might invade the fresh-water part of the aquifer from the south, and perennial spring flow in the Leona River valley would cease.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

The report on Uvalde County is one of several studies of the ground-water resources of the San Antonio area made by the U.S. Geological Survey in cooperation with the Texas Board of Water Engineers and the city of San Antonio. The San Antonio area as defined includes parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties within and adjacent to the Balcones fault zone. The purpose of the 1955–57 fieldwork was to collect additional basic data on the geology and occurrence of ground water in Uvalde County, especially in the aquifer formed by the Edwards and associated limestones.

The report contains geologic information on the character, thickness, depth beneath the land surface, and extent of the water-bearing formations. Existing maps and reports were studied and integrated with data from this investigation to determine the relation of local geologic conditions to the recharge, movement, availability, and quality of ground water in the county.

Plates 1 and 2 show the location of wells and springs in Uvalde County. The wells in the county have been numbered in accordance with an established grid system that has been used in a large area in south-central Texas. The quadrangles formed by the grid are identified by a letter and a number and the wells are numbered consecutively within each quadrangle. For example, all wells in the quadrangle containing the city of Uvalde are numbered H–5, followed by the individual well number. The grid system is one which was established many years ago based on latitude and longitude. The grid lines do not precisely accord with the parallels and meridians on the presently used base map. However, in order to preserve the original numbering system insofar as possible, it was decided to retain the old grid for well-numbering purposes.

The investigation was made under the direct supervision of R. W. Sundstrom, district engineer in charge of ground-water investigations in Texas.

METHODS OF INVESTIGATION

Fieldwork began in October 1955. Wells and springs were inventoried, selected samples of water were collected to be analyzed chemically, water levels in selected wells were measured periodically, and the geology of the water-bearing formations was studied. Many of the well records, chemical analyses, and water-level records have been included in a report by Petitt and George (1956, v. 2, pts. 2 and 3). The remainder of the records are on file in the offices of the Geological Survey in Austin, Tex. Outcrops of geologic formations were measured in detail, then traced downdip and correlated with subsurface equivalents by means of drillers' logs and electric logs. The surface geology was mapped on aerial photographs and transferred to a base map. A portable electric logger was used to log many wells during the investigation; electric logs were useful not only in correlation of formations but also in interpretation of some of the descriptive terms used in drillers' logs. Logs of wells were obtained from many drillers and well owners, and samples of well cuttings were taken from test wells drilled as part of the program. The cuttings were examined with a hand lens or a binocular microscope.

In many areas, geologic outcrops were used as control points for structural contours. Altitude control, used in preparation of subsurface geologic and hydrologic maps, was compiled from spirit and barometric leveling and from topographic maps.

PREVIOUS INVESTIGATIONS

Several investigations have been made of the geology and ground-water resources of Uvalde County and adjacent areas. Among the earliest detailed investigation was that of Hill and Vaughan (1898a), who mapped the Nueces quadrangle, which covers parts of northwestern Uvalde County and northeastern Kinney County, western Real County, and southeastern Edwards County. Vaughan (1900) mapped the Uvalde quadrangle, which covers the central part of Uvalde County and the northern part of Zavala County. Lonsdale (1927) described and igneous rocks of the Balcones fault zone, including part of Uvalde County. Sayre (1936) described the geology, hydrology, and ground-water resources of Uvalde and Medina Counties. Livingston (1947) reported on the relation of spring flow to the discharge of the Leona River. Petitt and George (1956) summarized the hydrology of Uvalde County in a progress report on the ground-water resources of the San Antonio area.

ACKNOWLEDGMENTS

The authors are indebted to farmers, ranchers, well drillers, city and county officials, and oil-company employees, who supplied information that aided in the investigation. Dr. Keith Young of the University of Texas identified fossils from some of the geologic formations. Mr. F. M. Getzendaner of Uvalde supplied geologic information and many well logs. The Shell Development Co. and Mr. W. F. Guyton furnished portable electric-logging machines that were used during the investigation. The authors express their appreciation for geologic assistance from Messrs. C. I. Smith, F. L. Stricklin, B. F. Perkins, and F. E. Lozo of the Shell Development Co., and Mr. R. T. Hazzard, formerly of the Gulf Refining Co.

LOCATION AND ECONOMIC DEVELOPMENT

Uvalde County, an area of 1,588 square miles in south-central Texas, is bounded on the east by Medina County, on the south by Zavala County, on the west by Kinney County, and on the north by Edwards, Real, and Bandera Counties (fig. 1). The county lies approximately between lat 29°05′ and 29°38′ and long 99°24′ and 100°07′. Uvalde, the county seat, in the south-central part of the county, is 80 miles southwest of San Antonio and 60 miles east of Del Rio on the Rio Grande.

The estimated 1957 county population was 20,000; the estimated 1957 population of the city of Uvalde—the business center for stock-raising and farming interests—was 12,000. Although manufacturing in Uvalde is of relatively minor importance, the city has the heaviest concentration of industry in the upper Nueces River basin. The chief products are agricultural insecticides, hen cages, and agricultural-aircraft tanks and hoppers. In 1957 Sabinal, Knippa, and Utopia had estimated populations of 2,600, 325, and 210, respectively. Other settlements have less than 100 residents.

About 13,000 acres of land was irrigated in 1956 and about 100,000 acres was dry farmed. Quarries in the western part of the county near Blewett make Uvalde County the largest producer of rock asphalt in the State. Other mineral resources are clay, limestone, gravel, and igneous rock used for road metal.

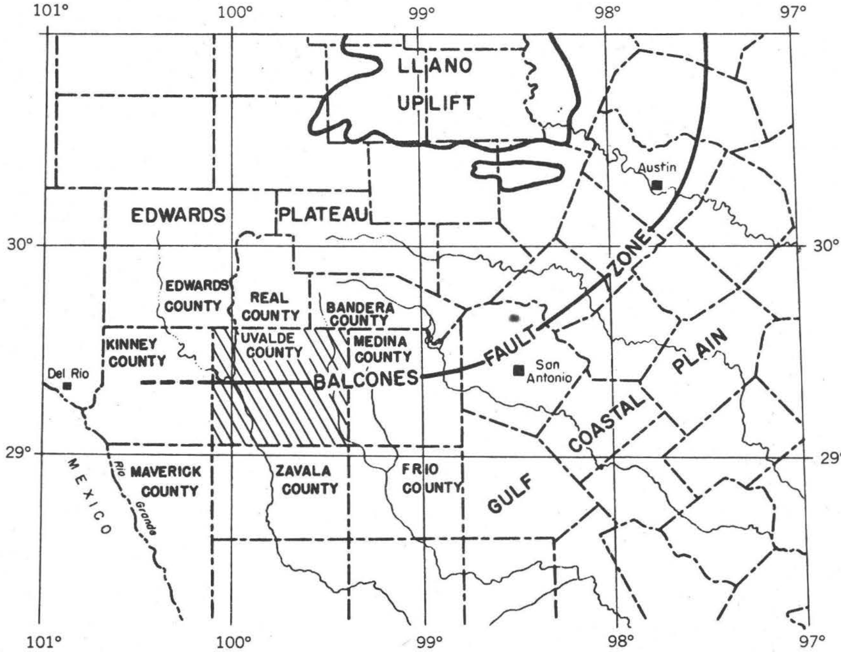

FIGURE 1.—Map of central Texas showing physiographic provinces and location of Uvalde County

TOPOGRAPHY AND DRAINAGE

Uvalde County occupies parts of two physiographic regions: in the north, the Edwards Plateau, and in the south, the Coastal Plain; the two regions are separated by the nearly eastward-trending Balcones fault zone (fig. 1). The plateau, on the upthrown side of the fault zone, is an area of high relief and much of the area is rough or rolling. Except for scattered heavy growths of juniper, the vegetation on the plateau is sparse. The Coastal Plain, on the downthrown side of the fault zone, consists primarily of undulating prairies and low hills. In places in the Coastal Plain rounded hills represent the remnants of igneous intrusions. Resistant sedimentary strata form low cuestas in the Coastal Plain; one of the most conspicuous of these is near Sabinal. The Coastal Plain supports an abundant growth of mesquite and other brush. Live oak, pecan, elm, walnut, and cypress grow in the flood plains and along the streams.

In general, the regional slope of the land surface is slightly east of south. The altitude ranges from about 700 feet above sea level where the Sabinal River leaves the southeastern corner of the county to 2,000 feet or more in the highest part of the Edwards Plateau. Near the south margin of the plateau the altitude is about 1,100 feet.

From west to east, the major streams in the county are the West Nueces, Nueces, Leona, Dry Frio, Frio, Blanco, and Sabinal Rivers. Most of the streams are spring fed in the plateau area; however, all the streams lose much of their flow while crossing some of the limestone units in the Balcones fault zone and are dry or flow intermittently after leaving the fault zone. In the southern part of the county the streams are fed by other springs in some places. The streams have dissected the plateau into high hills and deep, narrow valleys that have steep gradients. The shallow, broad valleys of the Coastal Plain have moderate to slight gradients.

CLIMATE

Uvalde County has a warm subhumid climate. The daily mean temperatures for January and July at Uvalde are about 53°F and 85°F, respectfully; the yearly mean is 69°F (fig. 2). The temperature in the winter is highly variable; daily maximums are rarely below freezing and extensive warm periods occur occasionally. The average growing season in Uvalde County is 248 days; the average date of the first frost is November 12 and the last frost is March 9.

The mean annual precipitation at the city of Uvalde for 1920–57 was 23.46 inches. The record of annual precipitation (fig. 2) shows that the maximum during the period was about 45 inches in 1932 and the minimum was less than 10 inches in 1956. Figure 2 shows that the precipitation is unevenly distributed throughout the year, most of it occurs during the spring and summer.

GEOLOGY

In Uvalde County, Cretaceous rocks lie on a basement complex of rocks of probable Paleozoic age, none of which are exposed in the county. Outcrops of sedimentary rocks, which range in age from Cretaceous to Recent, consist of limestone, chalk, caliche, conglomerate, gravel, sand, silt, shale, and clay. Intrusions of basalt and other dark-colored igneous rocks occur in the forms of plugs, sills, and stocks. Table 1 shows the lithologic character, water-bearing properties, and maximum observed thicknesses of the various formations.

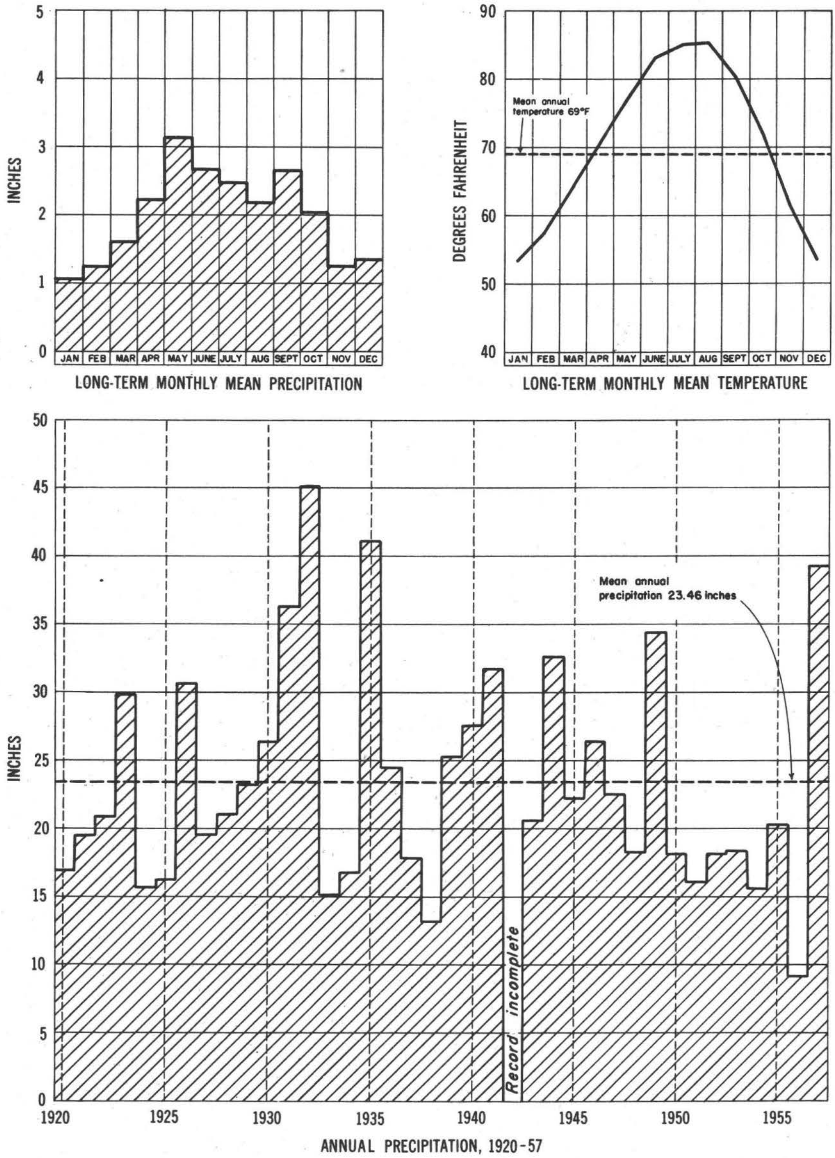

FIGURE 2.—Precipitation and temperature at Uvalde (from records of U.S. Weather Bureau).

TABLE 1.—*Rock formations and their water-bearing properties, Uvalde County, Tex.*

System	Series	Group	Formation	Maximum observed thickness (feet)	Lithology	Water-bearing properties
Quaternary	Recent and Pleistocene		Leona formation (includes Recent alluvium)	105	Silt, sand, clay, and gravel.	Yields small to large supplies of water.
Tertiary	Pliocene(?)		Uvalde gravel	20	Silt and coarse gravel.	Not known to yield water in Uvalde County.
	Eocene	Claiborne	Carrizo sand	50+	Coarse- to medium-grained sand and sandstone. Locally crossbedded. Contains a few quartzite ledges.	Yields small supplies of water.
		Wilcox	Indio formation	200+	Thin-bedded clayey sandstone and shale. Contains lignite and thin beds of bog iron ore.	Yields small supplies of water which is saline in most areas.
	Paleocene	Midway	Kincaid formation	25	Clay, siltstone, sandstone, and limestone. Thin conglomerate at base.	Not known to yield water in Uvalde County.
Cretaceous	Gulf		Escondido formation	285+	Hard fine-grained sandstone and interbedded shale and clay; some limestone.	Yields small supplies of saline water.
			Anacacho limestone	470	Fine to coarse-grained limestone alternating with red bentonitic clay.	Yields small supplies of saline water.
			Austin chalk	580	White to buff chalk, marl, and limestone.	Yields small to moderate supplies of water.
			Eagle Ford shale	240	Flaggy limestone and interbedded carbonaceous shale.	Yields small supplies of saline water.
	Comanche	Washita	Buda limestone	100	Hard massive fine-grained white to pink limestone; generally contains calcite veins and red and black specks.	Yields small to moderate supplies of water.

Cretaceous	Comanche	Washita		Grayson shale	120	Blue clay, weathers yellow. Contains some thin limestone and abundant *Exogyra arietina* (Roemer).	Not known to yield water in Uvalde County.
			Edwards and associated limestones	Georgetown limestone	400	Hard massive cherty limestone.	Principal aquifer in Uvalde County. Yields large quantities of water of good chemical quality.
		Fredericksburg		Kiamichi formation	210	Flaggy, cherty limestone, black petroliferous shale, and some dolomite.	
				Edwards limestone	100	Hard massive cherty limestone and some dolomite.	
				Comanche Peak limestone	90	Hard nodular light-gray limestone.	
		Trinity		Glen Rose limestone	1,530	Alternating beds of limestone and marl. Thick, massive beds of limestone in lower member.	Yields small supplies of water, which is saline in most areas.
				Travis Peak (subsurface Pearsall) formation	440	Sandstone, limestone, and shale.	Probably capable of yielding small supplies of saline water.
	Coahuila of Mexico	Nuevo Leon and Durango of Mexico		Sligo formation	210	Limestone. Some sandstone and shale.	Probably yields small to moderate supplies of saline water.
				Hosston formation	910	Red sandstone and shale. Some limestone and conglomerate.	Do.
Pre-Cretaceous rocks				?	?	Sandstone, limestone, shale, and slate.	Not known to yield water in Uvalde County.

The principal geologic formations from which Uvalde County obtains its water supply are, from oldest to youngest, the Glen Rose limestone, the Edwards and associated limestones, the Buda limestone, the Austin chalk, and the Leona formation. The formations crop out in east-west belts across the county; however, the continuity of the belts has been disrupted in places by faulting (pl. 1).

The beds dip generally toward the south and southeast at an angle steeper than the slope of the land surface, and thus the beds are beveled by the land surface. The regional dip of the Edwards Plateau is estimated to be 15 to 20 feet to the mile. In the Coastal Plain the multiple faulting of the Balcones fault zone and a thickening of the formations have increased the regional dip to about 100 feet per mile. In the vicinity of faults or in areas of strong folding the strata may have almost vertical dips.

ROCK FORMATIONS AND THEIR WATER-BEARING PROPERTIES

PRE-CRETACEOUS ROCKS

Rocks of pre-Cretaceous age are not exposed in Uvalde County; however, several oil tests have penetrated slate, shale, limestone, and sandstone, all of which are probably of Paleozoic age. In the northeastern part of the county, well B–9–16 reached Pennsylvania shale at a depth of 1,270 feet. In the north-central part of the county, slate, black limestone, and sandstone of Paleozoic age were found at depths of 1,723 to 3,930 feet in well B–8–1. Near the city of Uvalde, well H–5–199 reached Paleozoic rocks at 3,460 feet. In the southeastern part of the county, well I–4–36 penetrated pre-Cretaceous rocks at a depth of 4,400 feet. No water has been reported from rocks of pre-Cretaceous age in Uvalde County.

CRETACEOUS SYSTEM

The lowermost Cretaceous rocks in Uvalde County were deposited upon an eroded surface of Paleozoic rocks by a sea whose margin moved northward during Early Cretaceous time. The lower beds are composed principally of sand and conglomerate which are of different ages at different points along the line of advance of the sea. While the marginal sand and conglomerate were being deposited, equivalent beds of shale, limestone, dolomite, and marl, were being deposited downdip. As a result a wedge of sediments thickening seaward was built up.

PRE-COMANCHE ROCKS

Prior to 1945 the Cretaceous rocks in Uvalde County were divided into the Comanche and Gulf series, the Travis Peak formation of the Comanche series being regarded as the oldest formation of Cretaceous age. The Travis Peak was believed to be everywhere in direct contact with the underlying Paleozoic rocks. Imlay (1945, p. 1425) presented evidence that a wedge of older strata of Cretaceous age lies between the subsurface extension of the Travis Peak formation and the Paleozoic rocks downdip from the outcrop of the Travis Peak. He divided the Cretaceous rocks of southern Texas into the Coahuila (in Mexico), Comanche, and Gulf series (table 1). The pre-Comanche rocks were classified as the Hosston and Sligo formations and correlated with the Durango and Nuevo Leon groups of the Coahuila series of Mexico.

Hosston and Sligo formations

According to logs of several wells in Uvalde County the Hosston formation is composed principally of red sandstone and interbedded layers of shale and limestone. At the base the formation is conglomeratic; it rests upon rocks of Paleozoic age. The Sligo formation consists chiefly of limestone and interbedded layers of sandstone and shale.

The Hosston and Sligo together form a wedge which thickens southward. In well B–9–16 the reported thicknesses of the Hosston and Sligo were 349 and 30 feet, respectively. In well H–5–199, near the city of Uvalde, the reported thicknesses were 910 and 210 feet, respectively. The electric log of well I–4–36 indicates about the same thicknesses as in well H–5–199.

Not enough deep wells have been drilled in Uvalde County to determine in detail the stratigraphy and water-bearing properties of the Hosston and Sligo formations. Well I–4–36 taps these formations, producing saline water; however, some of the water probably comes from the overlying Pearsall formation and Glen Rose limestone. In the north-central part of the county, well H–2–16 tapped about 100 feet of the Hosston formation; however, the well also taps the Glen Rose limestone and Pearsall formation, and consequently no conclusions can be drawn as to the quantity or quality of the water in the Hosston. Well B–8–21 yields a moderate supply of water from about 85 feet of sand believed to be of Hosston age; however, the water is reported to be too highly mineralized for human consumption.

From the scanty data available it is probable that the Hosston and Sligo formations will produce only small to moderate quantities of saline water in Uvalde County.

COMANCHE SERIES

The Comanche series in Uvalde County is divided into three groups which, from oldest to youngest, are the Trinity, Fredericksburg, and Washita groups.

695–555 O—64——3

TRINITY GROUP

Travis Peak (subsurface Pearsall) formation

The Travis Peak (subsurface Pearsall) formation is the oldest of the Trinity group. Imlay (1945, p. 1441) states that the Pearsall formation is the subsurface equivalent of the Travis Peak and suggests that the term Travis Peak be confined to the outcrop. The formation does not crop out in Uvalde County; the nearest reported exposures are near the Guadalupe River in northwestern Comal County (George, 1952, p. 15).

In Uvalde County the Pearsall formation consists of shale, limestone, and sandstone. The contact with the underlying Sligo formation is sharp and easily recognized in well logs, whereas the contact with the overlying Glen Rose limestone is gradational; the contact is arbitrarily placed at the base of the massive limestone of the lower Glen Rose. The Pearsall formation forms a wedge which thickens southward from about 150 feet in well B–9–16 to 440 feet in well H–5–199.

Little is known concerning the water-bearing properties and quality of water in the Pearsall in Uvalde County. The only wells that tap the formation (H–2–16 and I–4–36) tap other strata also and the properties observed cannot be attributed entirely to the Pearsall. From observations in southern Bandera County it seems that the Pearsall formation might yield small supplies of saline water to wells in northern Uvalde County.

Glen Rose limestone

The Glen Rose limestone, the oldest formation exposed in Uvalde County, crops out in valleys in the Edwards Plateau where streams have cut through the overlying Edwards and associated limestones. The estimated thickness of the formation, according to the log of well B–9–16 and surface measurements, is 900 feet in the northeastern part of the county; whereas in well H–5–199 in the south-central part of the county, the formation is 1,530 feet thick.

In Comal County, George (1952, p. 17) arbitrarily divided the Glen Rose limestone into lower and upper members, this division is made at the top of a well-known fossiliferous zone called the *Salenia texana* zone. A persistent thin limestone bed at the top of the zone is characterized by the presence of numerous fossils of *Corbula texana* Whitney. For this reason the bed throughout south-central Texas is commonly referred to as the "Corbula." In Uvalde County the zone consists of about 20 feet of nodular marl containing many fossils of *Orbitolina texana* (Roemer), *Porocystis* sp., *Trigonia* sp., *Salenia texana* (Credner), *Hemiaster* sp., and worm tubes. The only known exposure of the zone in Uvalde County is in the northern part of the Sabinal River valley.

The lower member of the Glen Rose consists chiefly of massive fossiliferous limestone and interbedded layers of marl or shale. The upper member consists of clay and nodular marl alternating with thin beds of impure limestone. The upper member contains two beds of anhydrite, the lower anhydrite bed immediately overlies the *Corbula texana* bed. In the outcrop the anhydrite beds appear as highly leached brownish-yellow distorted dolomitic clay; weathering has removed most of the anhydrite. The anhydrite beds are easily correlated in the subsurface on electric logs because of the high resistivity of the anhydrite. In the northern part of the county the two zones are about 200 and 400 feet below the top of the formation.

Shallow water features such as ripple marks, crossbedding, mud cracks, lignite, and dinosaur tracks are found locally in the Glen Rose limestone. The lithology of the formation is remarkably uniform along the strike, and the entire sequence from lower massive limestones through the anhydrite zones and thin limestones of the upper member is stratigraphically persistent along the strike from Uvalde County northeastward at least to Hays County.

Because of the difference in the resistance to erosion of the marl and limestone layers, the Glen Rose limestone forms a characteristic terrace or stairstep topography. Along the Nueces River near the Edwards County line, about 350 feet of the upper Glen Rose forms stairstep slopes rising to the overlying limestones of the Fredericksburg group.

The sharp contact of the upper part of the Glen Rose limestone with the overlying Comanche Peak limestone is probably a disconformity. The contact is easily recognized in the subsurface in well cuttings and on electric logs by the lower resistivity of the Glen Rose (pl. 3). The difference between the rock types of the two formations is seen at exposures where the light-gray limestone of the Comanche Peak rests on the dark-gray to blue shale and marl of the Glen Rose.

In the Edwards Plateau, the Glen Rose limestone supplies small but sufficient quantities of water for domestic and stock use; elsewhere in the county the water in the Glen Rose is probably too saline for most uses. The quality of the water from the Glen Rose varies widely. Water from the deeper wells is generally saline, whereas water from springs or shallow wells is hard but otherwise of good quality. The two anhydrite beds in the Glen Rose yield water that is high in calcium and sulfate content and the two beds should be cased off in wells that pentrate them; otherwise the water produced may be too saline for some uses.

FREDERICKSBURG AND WASHITA GROUPS

The Fredericksburg group in Uvalde County includes, in ascending order, the Comanche Peak limestone, the Edwards limestone, and the Kiamichi formation. The Walnut clay, the lowermost formation of the Fredericksburg group, is probably absent from the county. The Washita group includes the Georgetown limestone, the Grayson shale, and the Buda limestone.

The contacts between the Edwards limestone, the Kiamichi formation, and the Georgetown limestone have not been mapped in Uvalde County and the formations are shown as a unit on the geologic map (pl. 1). The three formation names as used in this report represent rock units and the units may not be strictly correlative with the formations at their type localities.

The Comanche Peak, Edwards, and Georgetown limestones were considered a single hydrologic unit and referred to as the "Edwards and associated limestones" by Petitt and George (1956, p. 16). The term "Edwards and associated limestones" as used in this report includes all formations from the top of the Glen Rose limestone to the base of the Grayson shale.

Comanche Peak limestone

The Comanche Peak limestone consists chiefly of hard light-gray nodular limestone 60 to 90 feet thick. The limestone contains tubes formed by boring organisms, the tubes being filled with pellets of softer material. The nodular appearance of the formation is its most distinctive characteristic (pl. 4).

The Comanche Peak limestone crops out as a thin cap on hilltops, or as a belt along the valley walls in the southern part of the plateau where it is capped by the overlying, more massive Edwards limestone. The formation forms a rather even slope, slightly steeper than that of the gentle, stairstep slope of the underlying Glen Rose limestone. The fossil *Exogyra texana* Roemer occurs throughout the formation but is more abundant in the lower part.

The Comanche Peak limestone is not distinguished from the overlying Edwards limestone by well drillers; consequently the water-bearing properties of the formation itself are not well known. The properties of the Edwards and associated limestones, which include the Comanche Peak, are discussed later in this report.

Edwards limestone

The Edwards limestone is composed of massive lithographic to medium-grained limestone and a few beds of dolomite, the total thickness ranges from 50 to 100 feet. Chert is found in a few places in the limestone. The limestone contains miliolid foraminifers, rudistids, and small slender gastropods, probably *Turritella* sp., which, with *Gryphaea mucronata* Gabb, are common in the upper 20 feet (pl. 4). The miliolid limestone is harder and more massive and containing fewer bore tubes than the Comanche Peak limestone. A prominent basal ledge in the Edwards served as a mapping horizon in Uvalde County. Like the underlying Comanche Peak limestone, the Edwards crops out chiefly in stream valleys in the southern part of the Edwards Plateau.

The Edwards limestone is an important part of the aquifer formed by the Edwards and associated limestones. The water occurs chiefly in solution openings. Individual limestone beds are massive and competent and, consequently, are highly susceptible to fracturing associated with faulting. Secondary solution along the fractures has created a cavernous, honeycombed structure in many areas.

The yields of wells in the Edwards varies widely. In the area of the Edwards Plateau most wells yield only a few gallons per minute and in some places the Edwards is nonproductive. For example, wells H–1–5 and H–1–12 were drilled through cavernous limestone in the lower part of the Edwards but produce only from the underlying Glen Rose limestone. The small yields on the plateau result from the thinness of the saturated section. The thinness in turn, results from rapid drainage of the Edwards through springs, especially where the formation is topographically higher than adjacent streambeds.

South of the Edwards Plateau the Edwards limestone is completely saturated and the water occurs under artesian pressure. Here the yields of wells are much greater than on the plateau.

Kiamichi formation

A formation, tentatively referred to as the Kiamichi formation, overlies the Edwards limestone and crops out in the northwestern part of the county. The Kiamichi consists of thin to flaggy dark-gray to buff leached petroliferous limestone containing bedded and nodular flint and zones of solution breccia (pl. 4). In the upper half of the formation are several layers of black petroliferous shale. Intraformational folding may indicate the former presence of anhydrite which was later altered to gypsum, the folding being caused by the volumetric increase involved in the alteration of anhydrite to gypsum. At or near the outcrop the removal of the gypsum through weathering has left leached zones up to 5 feet thick. Downdip the gypsum content increases, as does the thickness of the flaggy limestone. In the subsurface the Kiamichi formation is identified by the dark sulfurous, petroliferous nature of the drill cuttings and by high resistivity in electric logs (well H–5–202, pl. 3).

The Kiamichi formation crops out in the Edwards Plateau, where it forms gentle topographic slopes having conspicuous vegetal zones. Fragments of *Gryphaea* sp. and *Oxytropidoceras* occur rarely in the flaggy beds. The upper contact of the Kiamichi is placed at the base of a limestone breccia about 10 feet thick.

The observed thickness of the Kiamichi in Uvalde County ranges from 155 feet in the outcrop to 210 feet in well H–5–202.

In the eastern and northeastern parts of the county the Kiamichi seems to lose its distinctive features; the flaggy beds interfinger with thicker limestone and dolomite beds which have not been distinguished from overlying and underlying beds. Electric logs of well I–1–17 and I–4–36 show many thin beds having high resistivities but no well-defined zone of high resistivity as in the western part of the county. The geologist's log of well H–3–23 suggests that the flaggy beds of the Kiamichi grade eastward into a reeflike miliolid limestone.

The water-bearing properties of the Kiamichi formation are not well known because the overlying Georgetown limestone also is tapped by most wells drilled to the Kiamichi. In general, in wells in which the Kiamichi is included in the producing section, the water is higher in sulfate content than in wells that tap only the Georgetown. For example, well G–9–3 produces saline water having a high sulfate content, most of which probably comes from the Kiamichi. Near Uvalde, however, wells H–5–207, H–5–144, and H–5–192 penetrated the Kiamichi and the quality of the water is good.

Georgetown limestone

Near the city of Uvalde in well H–4–71 the flaggy beds of the Kiamichi formation are overlain by about 380 feet of fine-grained white limestone containing flint, referred to in this report as the Georgetown limestone. In the vicinity of Chalk Bluff on the Nueces River 17 miles northwest of Uvalde, 320 feet of the Georgetown is exposed. Here the limestone contains flint beds and large nodules in the interval between 140 and 275 feet above the base. The lower 8 feet of the section consists of a matrix of fine-grained limestone containing angular fragments of sandy limestone as much as 3 inches long (pl. 4). The presence of a similar limestone breccia at a point 15 miles northwest of Chalk Bluff suggests a disconformity. The breccia is assumed to be the basal unit of the Georgetown. Near Leakey in Real County (pl. 4) rudistid reefs are common in the Georgetown, but they disappear westward. Near the south edge of the plateau, the white limestone of the Georgetown caps the highest hills and forms prominent cliffs which contrast with the darker, gentler slopes of the underlying formation.

The thickness of the Georgetown could not be determined on the outcrop; however, in the subsurface the thickness ranges from about 310 to 400 feet (pl. 3).

The Georgetown is highly fossiliferous in places, especially in the upper 100 feet. *Kingena wacoensis* (Roemer), *Pecten* sp., and large echinoids are common. Rudistids, chiefly *Caprina* and *Toucasia*, are found in many beds. Small spherical bodies that appear to be oolites are common.

The contact of the Georgetown with the overlying Grayson shale is easily discernible both in the subsurface and on the surface. In the subsurface the contact is shown by the prominent change in the resistivity curve of electric logs (pl. 3) and by the rapid change from limestone to shale in drillers' logs. On the surface the contact can be placed within a vertical interval of about 5 feet wherein the limestone of the Georgetown becomes progressively argillaceous and grades into the overlying Grayson shale.

Hydrologically the Georgetown limestone is the most important unit of the Edwards and associated limestones. Most of the large-supply wells in the county produce chiefly from the Georgetown. Where artesian conditions prevail, wells need be drilled no deeper than about 200 feet below the top of the Georgetown to obtain large quantities of water.

Grayson shale

The Grayson shale conformably overlies the Georgetown limestone and crops out in an irregular belt in the southern part of the Balcones fault zone and along a structural uplift east of Uvalde. Several small patches occur in downdropped fault blocks in the Edwards Plateau (pl. 1).

The Grayson is predominantly a blue clay which weathers to yellow or yellowish brown. Pyrite nodules and thin beds of limestone are scattered throughout the formation. A characteristic fossil, *Exogyra arietina* (Roemer), a small oyster shell shaped like a ram's horn, is abundant in the formation, especially in the lower part. In some places the shells are cemented into calcareous layers 1 to 6 inches thick. Because of the difference in lithology, fossil content, and electrical properties, the Grayson is easily distinguished from the underlying Georgetown limestone and overlying Buda limestone.

The yellow clay zone of the Grayson shale is conspicuous on aerial photographs because of its characteristic light color. The clay forms a slope below the protecting resistant Buda limestone. The upper part of the slope, which generally is steep, is sparsely covered with vegetation and has a thin veneer of shells and pyrite nodules that have weathered out of the clay and limestone beds. Gypsum is commonly found disseminated in the clay and as a coating on the shells. The lower part of the slope is a gently sloping or nearly flat surface generally mantled by alluvium and having an abundant growth of mesquite, catclaw, cactus, and grass.

The thickness of the Grayson ranges from about 70 feet near Sabinal to 120 feet at the Kinney-Uvalde county line (pl. 3). The average thickness in the vicinity of Uvalde is about 90 feet.

The Grayson shale is a confining layer that overlies the Georgetown limestone. It is not an aquifer in Uvalde County.

Buda limestone

The Buda limestone, uppermost formation of the Comanche series, lies unconformably on the Grayson shale and is overlain unconformably by the Eagle Ford shale of the Gulf series. The Buda crops out chiefly in the southern part of the Balcones fault zone, on the Frio River south of Knippa, in isolated spots east and south of Uvalde, and along the Nueces River west of Uvalde. Because of its resistance to erosion, the Buda limestone crops out in many places as low wooded hills and ridges or as caps on hills and bluffs protecting the underlying easily eroded Grayson shale. The Buda is a massive limestone between two formations composed chiefly of shale; the upper and lower contacts are distinctive and easy to recognize. The thickness ranges from about 70 feet near Sabinal to 100 feet near the Kinney-Uvalde county line (pl. 3).

The Buda limestone characteristically is a dense, very fine grained, massive limestone. Its color ranges from white to gray to pink; the weathered surface is generally smooth and light gray or brown, but it may have a white nodular appearance where exposed in streambanks. The limestone is brittle and breaks into small, angular pieces having smooth or slightly conchoidal surfaces. The fresh surface has a porcelaneous texture, many small red and black specks, and veins of crystalline calcite.

Near the city of Uvalde the Buda furnishes moderate quantities of water of good chemical quality for domestic and irrigation use. Elsewhere in the county the Buda produces only small quantities of water.

GULF SERIES

Eagle Ford shale

The Eagle Ford shale consists chiefly of laminated blue to black carbonaceous shale and thin beds of flaggy limestone which are fossiliferous in places. The lower 40 feet, exposed in the Sabinal River valley east of well H–3–23, is composed of brown weathered shale, some weathered volcanic material, and a few flaggy limestone beds lying unconformably on the Buda limestone. The nearby contact with the overlying Austin chalk also is probably an unconformity.

The contact with the underlying Buda limestone is sharp and easily distinguished. The upper contact is less easily distinguished because the upper part of the Eagle Ford contains a large proportion of limestone which closely resembles the lowest part of the overlying Austin chalk. The best exposure of the Eagle Ford is at the shale and limestone cliff about 80 feet high that forms the west bank of the Nueces River about 2 miles north of the Southern Pacific Railroad bridge. A mile farther north the contact with the underlying Buda is well exposed.

Electric logs show that the formation thickens progressively westward from about 75 feet near Sabinal to about 240 feet near the Kinney County line (pl. 3).

The Eagle Ford yields small quantities of saline water in Uvalde county.

Austin chalk

The Austin chalk unconformably overlies the Eagle Ford shale and, in turn, is overlain unconformably by the Anacacho limestone. The Austin consists chiefly of white to buff chalk, marl, and limestone. In the outcrop area the Austin consists generally of massive beds of limestone in the lower part, becoming thin bedded chalky and marly in the upper part. The Austin is very fossiliferous, and in several places the formation is composed principally of shells.

On the Sabinal River north of Sabinal, the upper part of the Austin consists of 90 feet of moderately hard white chalk exposed in a steep westward facing bluff of the river. The chalk is overlain by about 30 feet of soft chalk and marl which form a gently sloping bench. For mapping purposes the upper contact of the Austin was placed at the top of the marl section immediately underlying the red bentonitic clay of the Anacacho limestone. Details of the stratigraphy and lithology of the Austin are shown on plate 5.

Near Sabinal the Austin is about 275 feet thick and, like the older formation, it progressively thickens westward across the central part of the county to about 580 feet in well G-9-3 (pl. 3).

The Austin chalk yields small to moderate quantities of water to wells in areas in which it corps out and for a short distance downdip from these areas. The Austin yields large quantities of water to a few shallow wells in the area between the Nueces and Leona Rivers southwest of Uvalde and in the valley of Turkey Creek near Cline. Near Uvalde the Austin furnishes water to irrigation wells H-4-59 and H-5-164.

Anacacho limestone

In Uvalde County the Taylor marl is represented by a series of calcareous, argillaceous, and, in places, pyroclastic clays and marls interfingering westward with limestone. Hill and Vaughan (1898b, p. 240–241) named the limestone facies the Anacacho from exposures in the mountains of that name in southeastern Kinney and southwestern Uvalde Counties. No further subdivision is attempted in this report; the entire unit is mapped and discussed as the Anacacho limestone.

In most places in Uvalde County the lower beds of the Anacacho limestone consist of rusty-red clayey beds which may be water-laid volcanic deposits (Hazzard, 1956, p. 58). The clayey beds are overlain by beds of fine- to course-grained limestone alternating with clay strata. Some of the limestone is coquinal. A study of cuttings from well G–9–3 shows that the clay beds are bentonitic, apparently water-laid volcanic deposit. The interbedded limestones contain asphalt; the asphalt is quarried in the western part of the county. The Anacacho is fossiliferous in many places, the fossils being principally cephalopods, mollusks, and echinoids. Details of the stratigraphy and lithology of the Anacacho are shown in plate 6.

The range in thickness of the Anacacho was not determined; however, in well G–9–3 the thickness was at least 470 feet.

The Anacacho limestone yields only small quantities of water, most of which is saline. The bentonitic clay beds in the formation tend to absorb water and to swell during drilling; therefore they must be cased off to prevent caving.

Escondido formation

The Escondido formation, as referred to in this report, includes all the strata beween the Anacacho limestone and the rocks of the Midway group. The Escondido overlies the Anacacho conformably; the contact is gradational. The contact with the overlying Midway group represents the unconformity between Cretaceous and Tertiary rocks (pl. 7). The Escondido is poorly exposed in Uvalde County; however, the few exposures show that the formation consists chiefly of hard fine-grained sandstone and interbedded shale and clay, some of which contains pyroclastic material. In an outcrop at the old crossing of the Nueces River (Pulliam Bridge) is fine-grained asphaltic sand overlain by a strongly cemented limestone bed containing *Ostrea cortex* Conrad. A thick clay sequence, which contains sandy beds overlain by a thin clay zone containing *Ostrea cortex*, forms the west valley wall of the Frio River downstream from Black Waterhole. Details of the lithology of the upper part of the Escondido are shown on plate 7.

The thickness of the Escondido formation was not determined. The log of well H–9–9 shows 285 feet of the Escondido; however, it is not known whether the full section is present. According to Holt

(1959, p. 32) the Escondido is about 550 feet thick in southwestern Medina County.

The Escondido formation yields small quantities of saline water to a few wells in Uvalde County.

TERTIARY SYSTEM

PALEOCENE SERIES

MIDWAY GROUP

Kincaid formation

Vaughan (1900, p. 2) described sandstone and clay beds on the Kincaid ranch in the lower Frio River valley in Uvalde County as Eocene in age and named them the Myrick formation. Later Gardner (1933, p. 78) reclassified the beds as the Midway group of the Paleocene series and named them the Kincaid formation.

The Kincaid formation in Uvalde County consists chiefly of clay and siltstone and lesser amounts of fine-grained sandstone and fossiliferous limestone. A thin glauconitic conglomerate containing shell fragments and shark teeth is found at the base of the formation. Details of the lithology of the Kincaid are shown on plate 7.

The maximum exposed thickness of the Kincaid is about 25 feet on the northward-facing slope of Elm Creek near its junction with the Sabinal River. The formation as exposed there thins westward to about 11 feet at the Nueces River and is completely overlapped within a mile to the north, where the overlying Indio formation rests directly on the Escondido. The thickness of the Kincaid in the subsurface was not determined.

The Kincaid formation is not known to yield water to wells in Uvalde County.

EOCENE SERIES

WILCOX GROUP

Indio formation

The Indio formation of the Wilcox group unconformably overlies the Kincaid formation and overlaps it completely in the southwestern part of Uvalde County. The formation is poorly exposed in Uvalde County; the best exposures are along the Frio and Sabinal Rivers and in the high bluffs along the Nueces River in Zavala County.

The Indio formation is chiefly nonmarine in origin and consists of lenticular, thin-bedded clayey light-gray to buff sandstone and sandy shale. In some places it contains thin beds of lignite and bog iron ore. The sandstone is poorly cemented, except in a few places where well-cemented massive or crossbedded calcareous sandstone ledges occur.

The complete thickness of the Indio was not determined; however, it is estimated that 150 to 200 feet of the formation is exposed in various places along the Frio and Sabinal Rivers.

The Indio yields only small quantities of water, which is used chiefly for domestic and stock purposes. In many areas it yields only saline water.

CLAIBORNE GROUP

Carrizo sand

The Carrizo sand of the Claiborne group unconformably overlies the Indio formation and crops out in the southeastern part of the county. The Carrizo consists of poorly cemented coarse- to medium-grained nonmarine sandstone containing lenses of sandy shale. The sandstone beds are thicker than those in the Indio and locally they are moderately to strongly crossbedded. The sandstone is generally light gray on the fresh surface but weathers to yellow or tan. Ledges of well-cemented ferruginous sandstone and quartzite are exposed in places along the Frio River. The total thickness of the Carrizo was not determined , but it is estimated that the maximum exposed thickness in the county is about 50 feet.

The Carrizo sand yields small quantities of water of good chemical quality for domestic and stock use in Uvalde County. In Zavala County, where the full thickness is present, the formation yields large quantities of water for irrigation.

PLIOCENE(?) SERIES

Uvalde gravel

The Uvalde gravel was named by Hill (1891, p. 366–370) after the upland gravel and silt deposits in the vicinity of the city of Uvalde. According to Sayre (1936, p. 67) the Uvalde was deposited by southward-flowing streams in either late Pliocene or early Pleistocene time. In most places removal of fine-grained material and weathering have reduced the original alluvial unit to residual gravel, occurring either as loose pebbles and cobbles or as gravel embedded in caliche. In the area between the Nueces and Leona Rivers southwest of Uvalde the formation contains enough fine-grained and silty material to provide a soil suitable for cultivation.

After the Uvalde gravel had been deposited, uplift in the area rejuvenated the streams and caused them to dissect the formation and cut into the underlying bedrock. As downcutting continued, the Uvalde stood progressivly higher above stream level and the water table was progressively lowered. Much of the water was discharged by seepage and capillary action and was evaporated as it was discharged, the evaporation resulting in the deposition of caliche. The pebbles and cobbles composed of limestone were easily dissolved by the percolating water, whereas the flint cobbles were more resistant, so that now some of the Uvalde remnants consist of thin sheets of flint gravel. In many places where the gravel has been exposed to weathering, it assumes a typical red ferruginous coating. The various stages of alluvial weathering of the Uvalde are shown in places where loose red flint gravel grades downward into white caliche-cemented flint and limestone gravel.

Small hills capped by residual gravel mapped as the Uvalde rise above the cultivated plains between the Nueces River and the city of Uvalde. Other gravel remnants lie on the divide between the Leona and Frio Rivers, in the area immediately east of the Blanco River, and on hills flanking the lower part of the Sabinal River. Just east of the Medina-Uvalde county line an area of the Uvalde gravel, which reaches an altitude of 1,000 feet, forms a widespread plain topped with fine dark soil.

The Uvalde gravel does not occur at a specific altitude in different places but is found at various levels, all above the present streambeds. The exact thickness of the Uvalde was not determined; however, the formation is thin; the maximum thickness probably is less than 20 feet. Because of its thinness and high topographic position, the Uvalde is not water bearing in Uvalde County.

QUATERNARY SYSTEM

PLEISTOCENE AND RECENT SERIES

Leona formation

Hill and Vaughan (1898b, p. 254) applied the name Leona formation to "the deposit making the first wide terrace of the Nueces and Leona Rivers, below the level of the Uvalde formation, and for the flood-plain deposit extending westward from Uvalde on the Leona to the Nueces River." Although they exclude from this definition "a smaller terrace, some 10 to 20 feet below the Leona terrace level," for purposes of this report, all alluvium younger than the Uvalde gravel, including Recent allvium, is mapped as a unit and called the Leona formation. From a study of profiles across the principal streams in Uvalde County, it is apparent that the alluvium occupies terraces at many different levels in the county and that the name Leona formation does not represent material at a particular topographic position or of a specific geologic time interval. In the following discussion the deposits of several terraces are mentioned, but they are considered a part of the Leona formation as defined above.

Hydrologically the most significant areas of the Leona formation are those in the Leona River valley and in the area between the Nueces and Leona Rivers. Vaughan (1900, p. 3) noted that "the old flood plains of the Nueces and the Leona Rivers were in free communication across a strip of country about 4 or 5 miles wide." The strip is bounded on the south by highlands of the Cretaceous strata capped by the Uvalde gravel. Geologic evidence indicates that during late Pleistocene time the Nueces River flowed across this strip through the lowland now occupied by Garmon Slough, entering the present Leona River valley south of Mount Inge.

The ancient Nueces River formed a large meander loop that cut a scarp southward into the Austin chalk in the unnamed hill northeast of Tom Nunn Hill. The old north-facing cut bank is still preserved. During flood stage the river was diverted at this point into a smaller southward-flowing stream of higher gradient. During subsequent floods more and more water was diverted from the ancient Nueces into the modern Nueces valley. Eventually the river cut the canyonlike gap through the Austin outcrop northeast of Tom Nunn Hill, the gap restricting the modern Nueces flood plain to its narrowest width in the county. The increased flow southward down the new course of the river made less water available for flow southeastward into the Leona valley. As the flow into the Leona valley decreased, the carrying power of the stream likewise decreased and the old channel began to fill with clay and silt, ultimately forming a clayey confining layer overlying the older coarse gravelly material. Later a small southward-flowing stream, the present Leona River, flowed over the old clay fill, and cut the narrow channel which is the present course of the Leona River. The point of intersection of the tributary and the abandoned Pleistocene Nueces River channel is near the crossing of U.S. Highway 90 and the Leona River. The riverbed is wide and shallow north of the intersection, but at a point about 500 yards downstream from the bridge the channel narrows and deepens and has steep walls. The material in the channel walls consists of firm yellow silty clay containing scattered fossil bones. Downstream the yellow clay becomes more persistent and is found also in the riverbed. The Leona River flows on the yellow clay except in a few places where it has cut into the underlying gravel. At these points ground water emerges as spring flow when the gravel is saturated (Livingston, 1947, p. 13).

The relation of the Leona River to the Leona formation is shown on plate 8. The river is underlain by a large underflow conduit of gravel as much as 35 feet thick and 10,000 feet wide, which is overlain by a confining layer of yellow silty clay. Thus, the gravel is, for practical purposes, hydrologically independent of the river except at the spring sites. When saturated, the gravel acts as an artesian aquifer because of the presence of the overlying confining layer of clay; but, during periods of low water levels, water-table conditions prevail.

Large supplies of water are pumped from the Leona formation in the Leona River valley, and much of the water is used for irrigation. In 1946 the Leona furnished water sufficient to irrigate 1,950 acres in Uvalde County (Livingston, 1947, p. 5). The most productive wells are near the center of the valley where the gravel is deepest and thickest. At places near the edges of the valley the gravel rises slightly and thins and the wells in these areas are unreliable during periods when the water table is low.

In the vicinity of the city of Uvalde and in the plains area to the west, the Leona formation rests on highly permeable limestones of Cretaceous age, chiefly the Buda limestone and Austin chalk. During times of low water levels in the limestones, water entering the overlying Leona percolates into the limestones. Because of this fact, wells in the Leona are unreliable in this area during periods of drought.

At a point about 1 mile south of Mount Inge, faulting has downthrown the Cretaceous formations to the south so that the Leona formation is underlain by relatively impermeable serpentine and Upper Cretaceous and younger formations. In this area the underlying formations act as a confining layer and the wells here are relatively reliable during periods of drought.

The Leona formation yields water to wells in several other areas in the county. The area west and southwest of Uvalde between the Leona and Nueces Rivers is underlain by clay and gravel of the Leona formation; in places it exceeds 100 feet in thickness. The formation yields water to wells in this area when the water table is high; however, in times of drought most of the wells go dry. A large area of the Leona formation occurs along the Frio River where the formation is more than 70 feet thick in places and yields small supplies of potable water to wells. This area has not been tested for large supplies; however, such supplies might be available in the area south of Highway 90, where the Leona is underlain by relatively impermeable Upper Cretaceous formations. Other areas where small quantities of water are obtained from the Leona formation lie along the lower reaches of the Blanco and Sabinal Rivers.

IGNEOUS ROCKS

Intrusive igneous rocks occur in many places along the Balcones fault zone, and they are particularly abundant in Uvalde County. The igneous masses occur in many forms, but volcanic plugs, dikes, and sills are the most common.

The igneous rocks include basalt, phonolite, serpentine, and possibly volcanic ash. The most common type is basalt, which is resistant to erosion and forms prominent hills, mostly south of the Edwards Plateau.

Along the south edge of the Edwards Plateau, veins of siderite, limonite, and kaolin are found in the Glen Rose and Edwards limestones and small amounts of silver, gold, and other minerals are reported by Vaughan (1900, p. 5). The veins probably are products of liquid or gaseous emanations from parent magnetic bodies.

The rocks locally referred to as serpentine consist of soft green to yellow claylike material, which is probably an alteration product of basalt. Greenwood (1956, p. 171) described samples of serpentine collected in Uvalde County as follows:

Specimens selected for thin-section study range from the altered margin of the alkali peridotite, patently an igneous rock, through massive earthy material of uncertain origin, to stratified rocks which are clearly marine sediments. The microscope reveals relic igneous textures reminiscent of the peridotite in all specimens, but the degree of alteration is frequently unrelated to the megascopic appearance of the specimen and its proximity to fresh igneous rock * * * All sections show pseudomorphs after olivine . . . An x-ray diffraction powder photograph on hand-picked grains showed the characteristic pattern of a montmorillonoid . . . The groundmass, amounting to 75–90 percent of the rock, consists mainly of murky cryptocrystalline material with relics of brown hydrated glass corresponding to palagonite * * *

The soft serpentine material crops out commonly in stream beds and is found in great thicknesses in the subsurface. It is fairly easy to drill through except where intruded by basaltic sills and dikes. It does not cave as easily as may be expected, although casing generally is used as a precautionary measure.

The date of the igneous activity along the Balcones fault zone has been a matter of considerable speculation. Vaughan (1900, p. 5) first thought igneous activity took place in Eocene time, but later workers believed that most of the activity took place during Late Cretaceous time (Sayre, 1936, p. 28). The earliest evidence of igneous activity observed by the writers is a small amount of possibly bentonitic clay in the Eagle Ford shale. Thin beds of red bentonitic clay in the upper part of the Austin chalk in the Sabinal River valley (pl. 5) may be igneous in origin. The presence of bentonitic clay in the Anacacho limestone and Escondido formation certainly indicates igneous activity during Late Cretaceous time.

Basalt and serpentine were penetrated in many wells throughout the county. In wells H–4–91, H–5–255, and H–6–58, which are unproductive, the serpentine is several hundred feet thick. In others, such as H–4–38, H–4–48, and H–5–174, the drillers report several tens of feet of serpentine overlying sedimentary formations, and the yield of the wells does not seem to have been affected by the presence of the igneous rock. A few wells, such as H–5–242, H–6–39, and H–6–56, produce small quantities of water from basalt.

STRUCTURE

The principal structural feature in Uvalde County is the nearly eastward trending Balcones fault zone, a zone of faulting and some folding in which Lower Cretaceous limestones have been upthrown to the north, forming an escarpment that separates the Edwards

Plateau from the Gulf Coastal Plain. The displacement is greatest in the northeastern part of the county, where it totals about 700 feet. The displacement along single faults in this area exceeds 250 feet. In the southwestern part of the county the fault displacement diminishes and the zone becomes one of folding and jointing. Throughout the fault zone evidence of faulting is apparent, although the actual fault planes are rarely seen because of the surficial alluvial deposits. Thus the faults shown on the geologic map represent only a part of the total. All the faults observed are of the normal type and most of them are downthrown to the south, although a few are downthrown to the north. Some of the structural relations in the fault zone are shown on plates 3 and 9.

A prominent structural high associated with the Balcones fault zone extends southward from the Edwards Plateau; it occupies an area between the towns of Uvalde and Knippa. The high, known as the Uvalde salient, consists of several closely connected crustal uplifts where the Edwards limestone and other formations are brought to the surface, generally forming prominent hills. The uplifts which roughly bound the salient, are associated with basaltic masses that extend from Blue Mountain northwest of Knippa southwestward through Uvalde to Rocky Hill, thence eastward to Frio Hill. Large-scale faulting associated with the salient has dropped a block of the Escondido formation between blocks of older formations south of Black Waterhole, and to the north structural movement has exposed Upper Cretaceous rocks and serpentine in the bed of the Frio River.

Along the south edge of the Uvalde salient from Frio Hill west to Rocky Hill downwarping has lowered the Cretaceous formations to the south sufficiently to break the hydraulic continuity in this direction. This east-west zone of deformation is characterized by outcrops of basalt believed to be associated with faulting. Basalt crops out along the flanks of the salient north and southeast of Knippa and west and southwest of Uvalde. Another feature probably associated with the salient is a structural trough, the axis of which dips northeastward from Uvalde along Taylor Slough past Black Mountain where it turns eastward (pls. 1, 9).

No satisfactory method for determination of the time of the faulting has been found. Igneous bodies are found throughout the Balcones fault zone, and it seems that crustal deformation and igneous intrusion are closely related. In Uvalde County igneous outcrops coincide to a large extent with structural features. Sedimentary formations adjacent to outcrops of igneous rocks are invariably faulted and jointed, indicating that the intrusion took place after the bedrock had become consolidated. The presence of water-laid volcanic material in the upper part of the Austin chalk may indicate that crustal deformation had begun by late Austin time; basalt plugs in the Anacacho limestone and thick serpentine complexes in the Econdido formation suggest that most of the igneous activity and at least some of the faulting occurred near the close of the Cretaceous period. The movement along the fault zone was probably recurrent over a long period. The presence of the prominent escarpment along the fault zone indicates that at least part of the movement was fairly recent—perhaps during Pliocene or Pleistocene time.

GROUND WATER

PRINCIPLES OF OCCURRENCE

The source of all fresh water in Uvalde County is precipitation in the county and adjacent areas. The average annual precipitation in Uvalde County is about 23 inches, but only a small part of the precipitation reaches the ground-water reservoir. Precipitation falling on the earth's surface is either absorbed (infiltration), remains on the surface and runs off overland (direct runoff), is consumed by vegetation (transpiration), or is evaporated (evaporation). The part of the water that escapes direct runoff and evapotranspiration percolates slowly downward through the soil and underlying strata and joins the body of ground water in the zone of saturation, the top of which is the water table.

A formation, group of formations, or part of a formation that yields water in usable quantities is termed an "aquifer." In areas where it is difficult to obtain ground water, formations that yield only a few gallons per minute may constitute important aquifers. On the other hand, aquifers that yield a few gallons per minute may be considered nonproductive in areas where other aquifers are present that yield large quantities of water. The aquifers in Uvalde County consist of strata of Cretaceous age and of unconsolidated alluvial deposits of Quaternary age. The most important aquifers in the county are the Glen Rose limestone, the Edwards and associated limestones, the Buda limestone, the Austin chalk, and the alluvium and Leona formation.

The quantity of ground water available in an area is partly dependent upon the capacity of the rocks in that area to contain and transmit water. In turn, the capacity of the rocks to contain and transmit appreciable supplies of water is dependent in large part upon the size, shape, and arrangement of the openings they contain. Rocks differ widely in their ability to contain and transmit water. For example, shale and clay may contain large quantities of water but transmit only small quantities. On the other hand, cavernous limestone or sand and gravel may contain less water per unit volume of material but may transmit large quantities of water.

Most of the usable ground water in Uvalde County is contained in beds of limestone. Factors controlling the porosity and permeability of limestone include: the presence of solution openings, joints, and other fractures; the degree of cementation and compaction; and the shape and size of the particles. The openings in the limestones in Uvalde County are formed chiefly by fracturing and solution; the limestone is most permeable in areas where fracture openings have been enlarged by solution. In the Balcones fault zone, the thick, hard, very competent limestone beds in the upper and lower parts of the Edwards and associated limestones have large fracture openings and as a unit are highly permeable. The softer flaggy beds in the middle part, which are softer and less competent, are less subject to fracturing and as a unit are much less permeable. Furthermore, clay occupies the spaces between the limestone particles in the flaggy beds, thereby retarding solution. The hard, competent limestone beds in the Buda and in the lower parts of the Glen Rose limestone and Austin chalk are fractured; however, they transmit less water than the Edwards because of the thinness of the individual limestone beds and the smaller combined thickness of the beds.

Generally, solution channels in limestone are larger than those in dolomite because limestone dissolves more readily than dolomite. The Glen Rose limestone contains appreciable amounts of dolomite and is much less permeable than the Edwards limestone, some parts of which are nearly pure limestone. The Buda, like most of the Edwards, is a hard, nearly pure limestone, but it is much thinner and transmits much less water.

Water in contact with limestone is a fairly effective solvent because it contains carbon dioxide (carbonic acid) and other weak acids. In the zone of weathering, the rapid movement of storm water also erodes the weathered rock and enlarges solution channels.

Of the Quaternary sand and gravel aquifers in Uvalde County, only the Leona formation proper yields large quantities of water. The water in the Leona is contained in the spaces between the grains of the sand and gravel. The ability of the material to yield water depends chiefly upon the size and degree of interconnection of the intergranular spaces. In some places the sand and gravel of the Leona are apparently clean and are very permeable. In other places the intergranular space is partly filled with silt, clay, or caliche and the permeability is low.

Throughout most of Uvalde County the chief water-bearing formations are separated by relatively impermeable strata. For example, the upper part of the Glen Rose separates the more permeable lower part from the Edwards and associated limestones. The Grayson shale lies between the Buda limestone and the Edwards; the Eagle Ford shale lies between the Buda limestone and the Austin chalk.

In some places, however, the chief water-bearing formations are hydraulically connected. Where one aquifer has been faulted against another, water may be free to move between the two formations; freedom of movement is dependent upon whether impermeable material fills the space along the fault plane. Plate 3 shows that between wells H-4-71 and H-4-45 the Buda limestone is in fault contact with the Edwards and associated limestones. Plate 8 shows that the Leona overlies and is in contact with the Buda limestone. Such connections between the Edwards, Buda, Austin, and Leona formations probably exist in many places in the faulted area near the city of Uvalde (pl. 1).

Another possible type of hydraulic connection between the separated formations is through channels formed along fault planes. Again, freedom of movement is dependent upon whether impermeable material fills the faults.

RECHARGE

NATURAL

The aquifers in Uvalde County are recharged from precipitation within the county and from precipitation in the drainage basins of the streams that enter the county from the west and north. On the west the contributing area includes the northeast quarter of Kinney County; on the north it includes two-thirds of Edwards County, almost all of Real County, and a small part of western Bandera County.

The Edwards and associated limestones underlying the Edwards Plateau are drained by springs at the contact with the underlying Glen Rose limestone. The springs feed the streams that flow southward across the outcrop of the Glen Rose into the Balcones fault zone, where much of the flow is lost in the vicinity of the outcrop of the Edwards and associated limestones where they have been dropped down by the faulting. These stream losses constitute the greater part of the natural recharge to the Edwards and associated limestones, although some infiltration takes place directly from precipitation on the outcrop itself. Although some of the spring-fed streams are perennial and their base flow constitute a continual source of recharge, the total quantity of recharge from this source is small; most of the recharge occurs during periods of flood runoff. In some places gravel that overlies the Edwards and associated limestones may be recharged by the streams; the water is released slowly as it seeps into the limestone.

The potential recharge from the streams where they flow across the limestone outcrops is greatest where the streambed exposures in the intake area are longest. The lengths of streambed exposure in the outcrop of the Edwards and associated limestones are 13 miles along the Nueces River, 11 miles along the Frio, 14 miles along the Dry Frio, and 3 miles along the Sabinal. Most of the recharge from the West Nueces River moves from Kinney County into Uvalde County as underflow, the amount of the underflow being equal to the recharge less the withdrawals in the Kinney County part of the reservoir (if changes in storage are small).

Seepage from streams recharges other formations in the stream valleys, but to a lesser degree than the Edwards and associated limestones. Seepage studies on the Nueces River show that some streamflow is lost to the Buda limestone and the Eagle Ford shale, and a much larger amount is lost to the Austin chalk. The alluvium in some of the stream valleys is likewise recharged by seepage from streams. Such recharge to the Leona formation probably is slight, because the upper part of the formation is chiefly clay and silt and is nearly impermeable; water discharged from underlying formations is believed to be the chief source of recharge to the Leona.

The annual recharge to the Edwards and associated limestones in the fault zone was estimated for the 20-year period 1934–53 by Petitt and George (1956, v. 1, p. 21–41). By means of the method they describe, the record of annual recharge has been extended through 1957 for Uvalde County (table 2). Included in the estimate is water recharged in the West Nueces River basin, most of which enters Uvalde County by underflow from Kinney County. The mean annual recharge estimated for the period of record (170,000 acre-feet per year) is much greater than the mean annual recharge estimated for the drought period 1948–56 (100,000 acre-feet per year); this recharge indicates the severity of the drought. The period of drought is a

TABLE 2.—*Estimated annual recharge to the Edwards and associated limestones, Uvalde County, Tex.*

[Includes underflow from Kinney County]

Year	Recharge, in thousands of acre-feet	Year	Recharge, in thousands of acre-feet
1934	40	1946	150
1935	640	1947	160
1936	360	1948	90
1937	120	1949	280
1938	150	1950	90
1939	290	1951	50
1940	130	1952	50
1941	280	1953	40
1942	230	1954	90
1943	90	1955	190
1944	160	1956	20
1945	140	1957	320

substantial part of the period of record; therefore the "normal" annual recharge may be somewhat greater than 170,000 acre-feet—perhaps as much as 200,000 acre-feet per year.

ARTIFICIAL

An aquifer may be artificially recharged by water spreading or by injecting water through wells, pits, shafts, or other openings. The injection method has been used at several sites shown on Uvalde County (pl. 1), and though the economic feasibility of such projects is uncertain the problems are of interest.

Artificial recharging of limestone aquifers in the Balcones fault zone has been attempted by diverting floodwater into the fracture zones in limestone outcrops in streambeds. On the Mason ranch 16 miles north-northwest of Uvalde, local investigators found large northeastward-trending fractures in the bed of Indian Creek filled with soil, rocks, and organic debris. They discovered also that the fractures led into a large cave in the lower part of the Edwards and associated limestones. The authors, in 1956, found a tunnel in the cave; this tunnel averaged 6 feet in diameter, and sloped southward parallel to the bedding planes, about 20 feet above the top of the Glen Rose limestone. Two 8-foot-diameter holes were dug to the cave through the fill material in the fractures and were covered with steel grates to keep out logs and large rocks. A concrete dam nearly 8 feet high was built across the creek about 50 feet downstream from the cave to impound water and divert it into the cave. On the night of May 26, 1957, 5.2 inches of rain was recorded at the Mason ranch-house. On May 27, at 7 a.m. water began to rise behind the dam and flow into the cave. At 10:30 a.m. the water was flowing 2½ feet above the top of the dam and continued to do so for 1½ hours. The water ceased flowing into the cave by 6 p.m., approximately 11 hours after it began. On the basis of an assumed average hydrostatic head of 4 feet, the average velocity of flow into the cave was 16 feet per second. If it is assumed that the cross-sectional area of the shaft and fractures is 20 square feet, then the maximum rate of recharge would be about 320 cfs (cubic feet per second) or 144,000 gpm. At this rate during an 11-hour period, the total recharge would be about 290 acre-feet. This figure is the maximum possible and it is based on the assumption that the cave could take the entire flow without creating a condition of backwater. A smaller flood on May 31 completed the recharge at that site for 1957. It is estimated that the maximum recharge that could have taken place at the site during 1957 under the then existing conditions of precipitation and streamflow was about 500 acre-feet. This is about 0.29 percent of the total estimated average annual natural recharge in the county.

Another injection site in the bed of the Leona River about two miles north of Uvalde on the Kenedy ranch consists of a vertical shaft about 5 feet in diameter extending through the Grayson shale into the Edwards and associated limestones. Witnesses report that after heavy rains on October 22, 1957, a large but unknown quantity of water flowed into the shaft, although there is no dam to impound the water.

Two dams—one in the Leona River 1½ miles north of Uvalde and the other in the Sabinal River 2 miles north-northwest of Sabinal—are built on fractured zones in the Buda limestone. The Buda is separated from the Edwards by about 65 feet of nearly impermeable Grayson shale, and it is doubtful that the Edwards can be recharged appreciably at either of these sites.

On the John Garmon farm 4 miles southwest of Uvalde a 13-inch-diameter drilled well (H–4–94) is used as an injection well. Water impounded by an earthen dam across Garmon Slough flows along a canal into the well, which penetrates the Austin chalk. After the heavy rains of April 20, 1957, the canal, which is 10 feet wide, was opened, permitting the impounded water to flow into the injection well. On April 22, after the rate of injection had declined considerably, the rate was measured at 5,900 gpm; however, insufficient data are available to estimate the total amount recharged. At this time the water was carrying 0.13 ton of suspended sediment per acre-foot and the suspended load during maximum flow probably was much greater. Unless the recharge water is filtered, the sediment may reduce the rate of infiltration or completely plug the well.

The artificial-recharge program in Uvalde County amply demonstrates that water can be artificially recharged at high rates at least locally. However, the capacity, of existing impounding structures is too small to capture an appreciable proportion of the excess flood-flow of the streams in the county. Further studies are needed to determine the amount of excess water available annually for recharging; the type, number, and size of structures required to capture the excess water; and an economic determination of the feasibility of an expanded artificial-recharge program.

DISCHARGE

Ground water is discharged to the surface in Uvalde County through wells, springs, and seeps, and by evapotranspiration. Ground water is discharged from the county beneath the surface by underflow to the south and east. Most of the water discharged comes from the Edwards and associated limestones; although it is estimated that substantial amounts were discharged from the alluvium and

Leona formation and lesser amounts from the other water-bearing formations. The annual discharge to the surface from the Edwards and associated limestones for 1934–56, exclusive of underflow and of the county and of the relatively small amount consumed by evapotranspiration, is summarized in table 3.

UNDERFLOW

Annual discharge by underflow for the entire period of record cannot be estimated accurately because insufficient data are available to evaluate annual changes in storage. However, the average annual rate of underflow for 1934–47, when the net change in storage was small, was estimated to be 190,000 acre-feet by comparing the records of recharge and surface discharge. A part of the underflow (about 10,000 acre-feet) moves southward, chiefly through the alluvium and Leona formation along the Leona River valley; the rest moves eastward through the Edwards and associated limestones along the Balcones fault zone.

TABLE 3.—*Discharge to the surface from the Edwards and associated limestones, Uvalde County, Tex.*

	Millions of gallons per day						Thousands of acre-feet
Year	Municipal	Domestic and stock	Federal fish hatchery	Spring flow	Irrigation	Total	Total
1934	0.5	0.6	0.5	8.8	0.8	11.2	12.5
1935	.4	.6	.5	8.9	.3	10.7	12.0
1936	.5	.6	.5	21.4	.7	23.7	26.6
1937	.6	.6	.5	22.4	1.1	25.2	28.2
1938	.6	.6	.3	19.3	1.0	21.8	24.4
1939	.7	.6	.3	13.5	1.0	16.1	18.0
1940	.6	.6	.3	11.7	.9	14.1	15.8
1941	.6	.6	.3	13.4	.9	15.8	17.7
1942	.8	.6	.3	17.1	1.1	19.9	22.3
1943	1.0	.6	.3	13.5	1.5	16.9	18.9
1944	1.0	.6	.3	6.7	1.0	9.6	10.7
1945	1.0	.6	.3	7.3	1.6	10.8	12.1
1946	1.2	.6	.3	1.8	1.4	5.3	5.9
1947	1.4	.6	.3	8.0	1.8	12.1	13.5
1948	1.9	.6	.3	2.3	2.9	8.0	9.0
1949	1.4	.6	.3	4.5	4.8	11.6	13.0
1950	1.6	.6	.5	6.5	6.4	15.6	17.5
1951	2.3	.6	.5	.0	11.5	14.9	16.7
1952	2.5	.6	.5	.0	16.5	20.1	22.5
1953	2.8	.6	.7	.0	20.2	24.3	27.2
1954	2.8	.6	.8	.0	19.4	23.6	26.4
1955	2.9	.6	1.1	.0	20.7	25.3	28.4
1956	3.9	.2	.5	.0	48.2	52.9	58.2
Mean annual	1.4	.6	.4	8.1	7.2	17.8	20.0

DISCHARGE FROM SPRINGS AND SEEPS

Ground water is discharged through springs and seeps in Uvalde County where streams have cut below the water table in permeable formations (water-table springs) and where passageways are open to the surface from confined aquifers having a hydrostatic head above the land surface (artesian springs).

In the northern part of the county on the Edwards Plateau, water-table springs issue from the Edwards and associated limestones near its contact with the Glen Rose limestone. The flow of the springs maintains the base flow of the streams draining the Edwards Plateau. Most of the base flow is subsequently lost to the Edwards and associated limestones as the streams cross the Balcones fault zone where the Edwards has been dropped down.

The principal artesian springs are in the southern half of the county along the Leona River where the river has cut through relatively impermeable clays overlying gravel in the lower part of the Leona formation. The springs form the discharge points for the Leona formation and they flow only when there is excess water in the gravel in the lower part of the formation. The principal source of the water is the Edwards and associated limestones, which in some places is hydraulically connected with the gravel in the Leona. The record of the flow of the springs for 1934–56 is shown in table 3.

Many springs and seeps in the county issue from gravel deposits in the streambeds, chiefly in the Nueces River. Much of this spring flow represents an interchange between the flow of the streams and the underflow in the gravel. Where the gravel deposits are thin, water may flow on the surface; where they are thick, the surface flow may be wholly or partly lost and become underflow. The magnitude of the gains and losses of the streams has been demonstrated by seepage runs made in the principal streams (Petitt and George, 1956, v. 2, pt. 3, VI–1–VI–8).

WITHDRAWALS FROM WELLS

Table 3 shows that the largest use of ground water in Uvalde County since 1934 has been for irrigation, except in 1935. Although the first irrigation well was drilled in 1908, ground water was not used for irrigation in appreciable quantities until 1925. Irrigation increased gradually from 1925 to 1947; after 1947 it developed much more rapidly, withdrawals amounted to 48.2 mgd (million gallons per day), or 54,000 acre-feet in 1956 when about 100 wells were used to irrigate 13,000 acres.

Other uses of ground water in Uvalde County are small compared to the use for irrigation; however, ground water is the sole source for the municipal and industrial supplies and the chief source for domestic and stock supplies. In 1956 ground-water withdrawals averaged 3.6 mgd from 8 municipal wells at Uvalde and 0.25 mgd from 2 wells at Sabinal, a total municipal use of 4,300 acre-feet. During the same year about 560 acre-feet of ground water was used for fish and wildlife supplies and 220 acre-feet for domestic and stock supplies.

MOVEMENT OF GROUND WATER

Ground water moves in the general direction of the hydraulic gradient—that is, from points at which the altitude of the artesian head or water table is high to points at which it is low. The limestone aquifers in Uvalde County are not homogeneous; much of the movement of the water is along fractures and solution channels generally parallel to the fault pattern. The contours of the altitude of the water surface in the Edwards and associated limestones as shown in the piezometric map (pl. 10) show only the general direction of flow, which is eastward through the fault zone parallel to the faulting.

Some of the factors that control the configuration of the piezometric surface include the effects of recharge and discharge. Recharge tends to elevate the water surface in the recharge area; discharge tends to depress it in the discharge areas.

The piezometric map indicates that the information on geologic structure, quantitative measurements of recharge and discharge, and the general subsurface movement of ground water in the county can be described as follows:

Ground water in the Edwards Plateau moves from areas of recharge generally in the direction of surface drainage toward areas of discharge. From the principal areas of recharge on the outcrops of the Edwards and associated limestones south of the plateau, the water moves southward through solution channels; part of it is diverted eastward as it is intercepted by channels along faults. The water moving southward through the Edwards from the recharge area tends to be confined at the top by the Grayson shale, except where faulting has opened channels into overlying formations. Southward movement virtually ceases at the southern extent of faulting; water beyond this point commonly is saline.

Water moving eastward from the Nueces River basin follows devious paths, owing to the structurally high area of the Uvalde salient and the presence of intrusive igneous rocks. Eastward from well G–9–3 to well H–5–202 about 19 miles, the Edwards rises, not at a uniform rate but by means of complex faulting, on the Uvalde salient about 1,300 feet; from this point east it drops about 850 feet in 4 miles (pl. 9). The complex faulting in the area suggests that impermeable material may be in fault contact with the Edwards in some places, blocking or retarding eastward flow. On the other hand, faulting may have created a fracture system that facilitates flow in some places. The piezometric map (pl. 10) indicates that most of the movement is along the west and northern parts of the salient.

Water may move underground through the Leona formation between the valleys of the Nueces and Leona Rivers through a channel connecting the two stream valleys. The riverbed of the Nueces at the west end of the channel is at least 30 feet higher than the base of the gravel at a point near the east end. Thus the channel, which approximately underlies Garmon Slough, provides a possible avenue for subsurface movement of water from the Nueces River to the Leona River valley.

Under certain conditions water may move through the gravel deposits toward either the Leona River or the Nueces River from an area south and west of Uvalde. Altitudes of water levels in wells and subsurface geologic information indicate that near wells H-4-45 and H-5-163 the Edwards and associated limestones and Austin chalk are hydraulically connected with the Leona formation. Thus, when the piezometric surface in the limestone aquifers is above the base of the Leona, water probably spills out into the gravel of the Leona and moves toward either stream, according to where the spill occurs.

The principal limestone aquifers (Edwards and associated limestones, Austin chalk, and Buda limestone) are hydraulically connected with the Leona formation also in the Leona River valley just south of Uvalde. When the piezometric surface of the limestone is above the base of the Leona, water probably spills out into the gravel and moves downstream. When the piezometric surface is below the gravel, water entering the gravel from the surface probably drains into the limestone aquifers.

The interchange of water between gravel and bedrock formations in the Leona River valley ceases abruptly downstream between wells H-5-230 and H-5-255, where the bedrock changes from Austin chalk to serpentine. Plate 8 shows that the piezometric surface along the Leona River is continuous across the igneous-limestone contact when water is being discharged from underlying formations, but that hydraulic continuity is broken at the contact when water is being discharged to the limestone formations. During periods of drought the part of the gravel overlying the serpentine may contain water long after the gravel overlying the limestone has been drained.

Springs issue from the streambed of the Leona River when the storage capacity of the gravel is exceeded and where the river has cut into the gravel. The principal springs are just southeast of the city of Uvalde and at points 2 miles, 5 miles, and 9½ miles downstream. The southernmost springs are the first to flow as the water level in the gravel rises. The water level in well H-5-1 (pl. 11) correlates with the flow from two of the springs as measured at a stream-gaging station 4.6 miles southeast of Uvalde. When the water level in the well drops below 42 feet, the springs above the gage cease flowing.

FLUCTUATIONS OF WATER LEVELS

Water levels have been measured regularly in a few observation wells in Uvalde County since 1929 and in several others for varying lengths of time. A continuous water-stage recorder has been in operation on well H–5–1 since 1938, and others have been maintained on other wells for much shorter periods. Most of the water-level data are from wells that tap the Edwards and associated limestones, although a few long-term records are available for wells that tap the Austin chalk and the Leona formation. Miscellaneous measurements are available for a few wells that tap the Buda and Glen Rose limestones. Hydrographs showing fluctuations of water levels in wells that tap the principal aquifers are shown on plate 11 and on figure 3.

Water levels in wells fluctuate chiefly in response to changes in ground-water storage and reflect changes in hydrostatic pressure. Other water-level changes commonly observed in artesian wells in Uvalde County include those caused by changes in loading, by changes in atmospheric pressure, and by earthquakes. These changes do not reflect changes in the amount of water in storage; they are of relatively short duration, are small in magnitude, and are not detectable when plotted to the scale shown on the hydrographs in this report. Thus, the graphs in figures 14 and 15 represent chiefly the changes in storage caused by changes in the rates of recharge and discharge.

EDWARDS AND ASSOCIATED LIMESTONES

Plate 11 shows that the water levels in wells that tap the Edwards and associated limestones generally rise and fall at the same times, but the changes generally are greater in wells in the eastern half of the county than in the western half. Water levels in wells H–4–6, H–5–1 and H–5–22, in and west of Uvalde declined about 60 feet from the winter of 1941–42 to the winter of 1956–57; those in wells H–2–4 and H–6–16 in the eastern part of the country declined more than 100 feet during the same period.

The prolonged decline of water levels in wells beginning in 1950 shows the depletion of ground-water storage during the drought, when water levels declined steadily for nearly 4 years. During 1954–56 recharge in the Nueces River basin nearly halted the decline in the western half of the county; water levels in the eastern half of the county, however, continued to decline until the spring of 1957, although at a much slower rate after 1953. Water levels throughout the county rose rapidly during 1957 when above-normal precipitation broke the drought. In 9 months, water levels in wells rose an average of about 30 feet, demonstrating the remarkable capacity of the aquifer to refill rapidly.

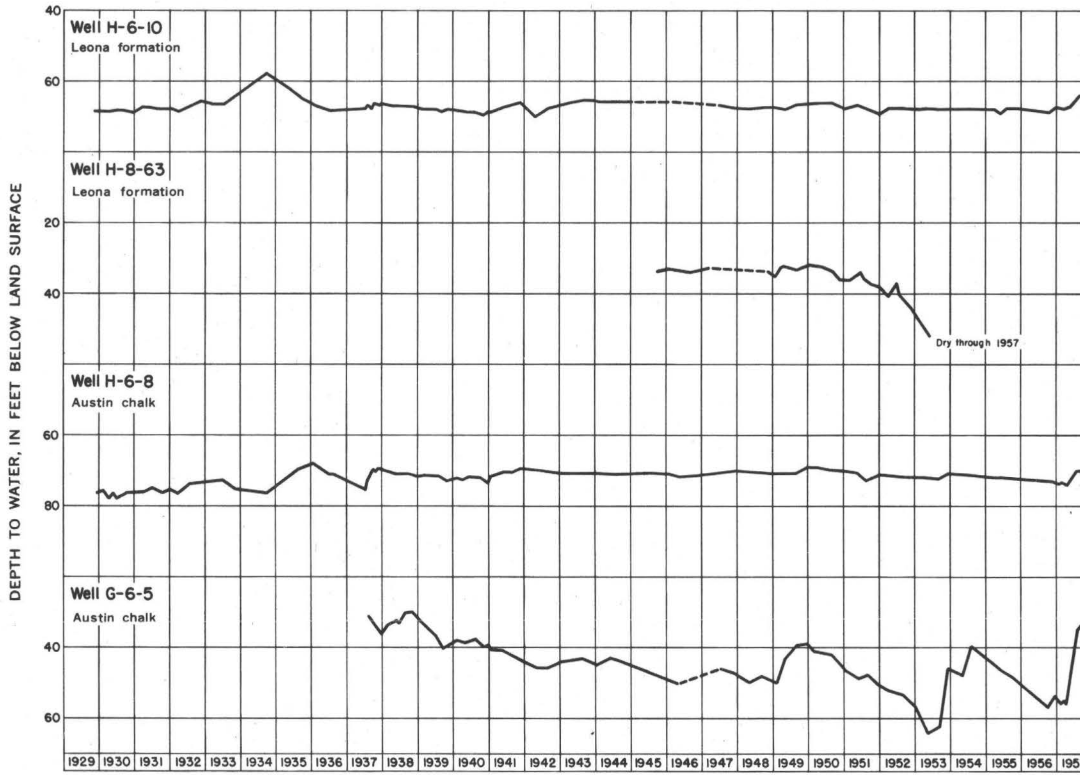

FIGURE 3.—Fluctuations of water levels in representative wells tapping the Leona formation and Austin Chalk, Uvalde County, Tex.

Table 3 shows that withdrawals of ground water increased substantially during the drought. In 1956 the underflow out of the county to the east probably was somewhat less than the average for 1934–47 (about 180,000 acre-feet; see p. 34). Thus, an appreciable part of the decline in water levels was caused by an increased rate of pumping.

LEONA FORMATION

Figure 3 shows the fluctuations of water levels in two wells that tap the Leona formation, well H–6–10 in the Sabinal River basin and well H–8–63 in the Leona River valley. The Leona formation in the vicinity of well H–6–10 is underlain by the relatively impermeable Anacacho limestone, which acts as a barrier to movement of water between the Leona and underlying limestones. The fluctuations of water level in well H–6–10 suggest that the Leona formation drains and is recharged slowly, drainage being somewhat more rapid when the aquifer is nearly full. The drought caused only a slight decline of water level in the well.

Near well H–8–63, the Leona formation probably is underlain by the Buda limestone or Austin chalk. The Leona formation is hydraulically connected not only with the Buda and Austin but also with the Edwards and associated limestones in the Leona River valley; consequently, water-level fluctuations in the limestone formations affect water levels in the Leona. After the springs ceased flowing in 1950, water levels in wells in the Leona formation fluctuated like those in the limestone formations. During the drought, water in the Leona was partly drained into the underlying formations, causing well H–8–63 to become dry early in 1953.

AUSTIN CHALK

Figure 3 shows the fluctations of water levels in two wells that tap the Austin chalk, well H–6–8 in the Frio River basin in the eastern part of the county and well G–6–5 in the Nueces River basin in the western part of the county. The rapid rise of water level in well G–6–5 after periods of above-normal precipitation suggests that the recharge characteristics of the Austin chalk in the western part of the county are similar to those of the Edwards and associated limestones. The fluctuations in the Austin, however, are much smaller than those in the Edwards and associated limestones, probably because of less favorable opportunities for recharge to the Austin. The Austin underlies a shorter reach of the Nueces River than the Edwards and furthermore is exposed farther downstream where the streamflow is much less than in the reach underlain by the Edwards.

Water-level fluctuations in well H–6–8 suggest that in the eastern half of the county the Austin chalk drains and is recharged at a much slower rate than in the western half. During 1938–57 the water level in well H–6–8 fluctuated through a range only about one-seventh as great as in well G–6–5. The reason for the difference is not apparent.

QUALITY OF WATER

The data on chemical quality of water in this report are compiled from 130 analyses made by the U.S. Geological Survey and from 8 analyses made prior to 1940 by the Works Progress Administration under the supervision of the Bureau of Industrial Chemistry of the University of Texas. The analyses made by the Works Progress Administration show the general chemical character of the water but do not conform to present-day standards of accuracy. Hence, comparison of them with analyses made by the Geological Survey will not necessarily show changes in quality where the difference between the reported quantities of individual constituents is slight. Wells and springs for which analyses of samples of water have been made are indicated by a bar above the well number on plates 1 and 2. Some of the analyses were included in a report by Petitt and George (1956, v. 2, pt. 3, p. IV–6, IV–7) and all the analyses are on file in the office of the Quality of Water Branch, U.S. Geological Survey, Austin, Tex.

Several factors determine the concentration and character of mineral constituents in ground water. The most important factors are the source of the water, the mineral composition of the rocks through which the water has passed, and the length of time the water has been in contact with these enclosing rocks.

Precipitation dissolves some gases and mineral matter from the air as it falls. After the water reaches the land surface, it becomes increasingly mineralized as it dissolves part of the material over or through which it flows. The water may dissolve sufficient material to render it saline and unsuitable for most uses. For purposes of this report, water containing more than 1,000 ppm (parts per million) of dissolved solids is considered saline.

During periods of overland runoff, the water in the streams has a lower mineral content than when the flow is sustained by springs. Although surface water is subject to sudden changes in quality during and after storms, the total range in dissolved mineral content in Uvalde County is much less for surface water than for ground water. Because available data indicate that all surface water in Uvalde County is fresh and suitable for most uses, no further mention of its mineral content will be made.

Certain relations of the depth of occurrence of ground water to its quality have been observed, the water from deeper wells generally is more highly mineralized than water from the shallower wells. All samples, except one, from wells that tap the Edwards and associated limestones at depths of less than 600 feet contained between 200 and 400 ppm of dissolved solids. These are calcium bicarbonate waters having only small concentrations of magnesium, sodium, sulfate, and chloride. The dissolved-solids content of samples from greater depth differed widely from place to place, ranging from 226 to 4,510 ppm. Increased concentrations of magnesium, sodium, sulfate, and, in some places, chloride, are found in the more highly mineralized samples. Plate 12 shows the dissolved-solids, sulfate, and chloride content of water from selected wells that tap the Edwards and associated limestones in Uvalde County. The figure shows also the approximate downdip limit of occurrence of fresh water in the Edwards.

All the water samples from the Leona formation were fresh. Water from depths greater than 300 feet in the Glen Rose limestone was saline, having high concentrations of calcium, magnesium, and sulfate. Sampling from other formations was inadequate to show any relation of quality to depth.

The suitability of a water for various uses is determined largely by the kind and amount of dissolved mineral matter it contains. Some chemical constituents when present in excessive concentrations may adversely affect the use of water for drinking, others for domestic and industrial purposes, and still others for irrigation. Only the chemical constituents most commonly found in undesirable concentrations in water in Uvalde County are discussed in this report.

Some of the wells that tap the Edwards and associated limestones yield water containing hydrogen sulfide. Even in small amounts it gives water an offensive odor and in larger amounts it is corrosive to metal. Hydrogen sulfide can be removed by aeration and, therefore, is not a serious problem in the use of the water.

The quality tolerances of water for drinking differ with individuals, but the standards established by the U.S. Public Health Service (1946, p. 382–383) for drinking water used on interstate carriers are generally accepted as criteria for judging the suitability of a water for drinking. The following chemical substances preferably should not be present in excess of the following concentrations:

Magnesium (Mg) should not exceed 125 ppm.
Chloride (Cl) should not exceed 250 ppm.
Sulfate (SO_4) should not exceed 250 ppm.
Fluoride (F) must not exceed 1.5 ppm.
Dissolved solids should not exceed 500 ppm. However, if such water is not available, a dissolved-solids content of 1,000 ppm may be permitted.

Some communities use water that contains certain minerals far in excess of concentrations suggested in the standards because better water is not available. The Public Health Service standards were set primarily to protect travelers from the ill effects of consuming water of markedly different chemical characteristics. Water having a chloride content exceeding 300 ppm tastes salty to most people. Water containing large quantities of magnesium and sulfate tends to have a laxative effect. Use of drinking water having a fluoride content exceeding 1.5 ppm may cause mottling of the teeth of children (Dean, Dixon, and Cohan, 1935, p. 424–442); however, the use of drinking water that contains about 1.0 ppm appears to reduce the incidence of tooth decay in children (Dean, Arnold, and Elvove, 1942, p. 1155–1179).

Water containing more than about 45 ppm of nitrate has been related (Maxcy, 1950, p. 271) to the incidence of infant cyanosis (methemoglobinemia or "blue baby" disease) and may be dangerous for infant feeding. The nitrate content of water may be an indication of pollution by sewage or other organic matter. A well that yields water containing more nitrate than others nearby should be tested for bacterial content of the water.

Most of the water used for public supply in Uvalde County meets the U.S. Public Health Service standards. The water from municipal wells at Uvalde was of excellent quality for drinking, although hard. At Sabinal, municipal wells yielded water that meets the drinking-water standards. Water from the Utopia school well (B–9–4), which taps the Glen Rose limestone, exceeded the suggested concentrations in the standards for dissolved solids, magnesium, sulfate, and fluoride. A sample from the Knippa school well (H–6–26) contained 108 ppm of nitrate; the high content of nitrate suggests that the water may be polluted.

Although sampling was inadequate to evaluate the water from each formation, the results suggest that the dissolved-solids, fluoride, and sulfate content of water in many places in the Glen Rose limestone and older formations is likely to exceed the suggested maximum concentrations in the drinking-water standards. The data suggest further that in a few places younger rocks contain water having excessive amounts of some of the constituents, especially fluoride and iron. Of 19 determinations of fluoride in water from wells tapping the Edwards and associated limestones, 2 were more than 1.5 ppm. The two samples came from depths greater than 900 feet, suggesting that water from shallow wells may not contain excessive amounts of fluoride.

Certain concentrations of calcium, magnesium, silica, iron, and manganese in water affect its use for industrial and domestic purposes. Calcium and magnesium cause virtually all the hardness of natural waters. As hardness increases, soap consumption increases and incrustations (boiler scale) accumulate in boilers, pipes, and coils more rapidly. Hardness equivalent to the bicarbonate and carbonate content is called carbonate hardness; the remainder is called noncarbonate hardness. Two methods are commonly used to soften large quantities of water: the lime or lime-soda process which, in addition to softening, reduces the content of dissolved solids; and the zeolite process, which involves the exchange of calcium and magnesium in the water for sodium in the exchange material. Carbonate hardness may be removed most economically by using lime as the precipitant. The analyses of water from Uvalde County may be compared with the following arbitrary classification commonly used to describe waters with reference to hardness:

	Parts per million
Soft	<60
Moderately hard	60–120
Hard	121–200
Very hard (water needs to be softened for most uses)	>200

The water samples indicate that nearly all the water in Uvalde County is hard or very hard. The few samples having a hardness of less than 120 ppm either came from formations of little importance or were not necessarily representative of the formation from which they were taken. The hardness of water in the limestone formations is largely carbonate hardness; the water, therefore, can be softened successfully with the lime process.

Because silica forms a hard, adherent scale in boilers, information as to its concentration in water supplies for boiler use is important to industries. Moore (1940, p. 263) has suggested the following allowable concentrations of silica in water for boilers operating at various pressures.

Concentration (ppm)	*Boiler pressure (pounds per square inch)*
40	<150
20	150–250
5	251–400
1	>400

The silica content of all the samples collected in the county was less than 50 ppm, and in most it was less than 20 ppm.

Oxidation of dissolved iron and manganese in water forms a precipitate that stains fabrics, utensils, and fixtures. Water containing more than 0.3 ppm of iron and manganese together is likely to cause appreciable staining. Only a few determinations of iron and manganese were made on ground-water samples, but enough showed concentrations of more than 0.3 ppm to suggest that these constituents may be a problem in parts of the county.

Water becomes less suitable for irrigation as the salinity and the sodium and boron content increase. Of these, only the salinity hazard appears to warrant attention in Uvalde County. Wilcox (1955, p. 16) reported that water may be used safely for supplemental irrigation if its conductivity (a measure of the salinity) is less than 2,250 micromhos per centimeter at 25° C. Judged by this criterion, most of the water in the Edwards and associated limestones is suitable for irrigation. However, in the southern part of the county the water in the Edwards becomes too saline for irrigation and most other uses. The approximate boundary between fresh and saline water in the Edwards is shown on figure 16.

The observed temperature of ground water in Uvalde County ranged from 69° to 93°F. The lowest temperature was measured in a spring and the highest in water from a well about 1,400 feet deep. No distinct relation of water temperature to well depth is apparent from the temperatures observed, the temperature of the water from the deepest well is only 76° F.

POTENTIAL DEVELOPMENT OF GROUND-WATER RESOURCES

Plans for the development of water from the Edwards and associated limestones in Uvalde County must be considered in relation to programs for the development of ground water throughout the entire area underlain by the aquifer. The area extends along the Balcones fault zone in parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties in a strip ranging from 5 to 40 miles in width. The strip, about 200 miles long, extends from a point about 35 miles west of the city of Uvalde to about 60 miles northeast of San Antonio.

Any program for the development of ground-water resources must consider plans for the development of surface water also. Much of the annual streamflow in Uvalde County represents ground-water discharge. In the northern part of the county the rivers are fed by springs. The rocks of the Edwards Plateau store water which drains out to form the base flow of the streams that have cut their channels into or through the aquifer. The streams flow southward on beds of the Glen Rose limestone until they cross the fault zone, where most of the water seeps into the Edwards and associated limestones and becomes part of the main ground-water reservoir.

One of the first problems to be considered in evaluation of the potential development of ground water in Uvalde County is the effect that the development will have on potential development elsewhere in the aquifer. A large part of the water recharging the Edwards and associated limestones moves eastward through interconnected fractures and solution channels along the fault zone and is discharged through wells and springs in and northeast of the city of San Antonio. Thus, water withdrawn from wells in Uvalde County will reduce the availability of ground water in areas east of the county. Withdrawals within Uvalde County may also reduce the quantity of surface water available to countries to the south. Withdrawals of ground water west of Uvalde County will reduce the quantity of ground water available within the county. Where water levels in the Edwards and associated limestones are above stream level, a substantial part of the streamflow is made up either of water that would otherwise recharge the aquifer or of water that is discharging from the aquifer. When pumping lowers the water levels below stream level, the water is lost from the streams to the aquifers.

The regional hydrology as it pertains to the occurrence and development of ground water in the Edwards and associated limestones has been described by Petitt and George (1956). The possibility of future development of water supplies in Uvalde County is discussed in the following paragraphs.

In Uvalde County, during the 23-year period 1934–56, the mean annual recharge (170,000 acre-feet) exceeded the mean annual discharge to the surface (20,000 acre-feet) by 150,000 acre-feet. The decrease in storage shown by the decline in water levels during the period indicates that a large amount of water left the county by underflow. Most of the water flowed eastward into Medina County, although prior to 1951 about 10,000 acre-feet per year moved southward.

The loss in storage and the amount of the underflow eastward can be computed from recharge and discharge estimates for the entire San Antonio area and from water-level fluctuations in wells in Uvalde County. The underflow into Medina County for a particular period of time may be considered the difference between the amount of recharge and the amount of surface discharge plus or minus the change in storage in the aquifer west of the Uvalde-Medina county line; similarly, the recharge-discharge-storage relationship east of the county line also can be used to determine the underflow. During 1934–47, when the storage loss was small, the difference between recharge and discharge in the western part of the aquifer averaged about 190,000 acre-feet per year; the difference in the eastern part was about 230,000 acre-feet per year. By considering the average water-level declines and the areal extent of the western and eastern parts of the aquifer, the storage loss appears to have been somewhat less in the western part than in the eastern part. Thus, the average underflow for 1934–47 was probably close to 200,000 acre-feet per year.

Ground-water withdrawals in Uvalde County probably could be maintained indefinitely at a rate equal to the "normal" rate of recharge (about 200,000 acre-feet per year) if the water resources north and west of the county are not further developed. Eventually, however, continued withdrawals at this rate would cause a decline of water level to a depth where wells in structurally high areas would be dry and underflow into Medina County would cease. The lowering of the water levels in the aquifer might also cause saline water to move from downdip or from other formations into the Edwards. Water-level declines would also cause perennial spring flow in the Leona Valley to stop.

Potential development of the total water resources may be increased by artificial recharge. Studies to date suggest, however, that the amount that can be recharged economically is small compared to the present potential. The erratic occurrence of storms and variations in the rate of runoff complicate the planning of recharge projects. The quantity of water that can be salvaged by artificial recharge is the amount saved from evaporation and runoff to the sea. The rest merely depletes surface supplies to increase ground-water supplies.

The potentially developable water supplies from the Glen Rose limestone, Buda limestone, Austin chalk, and Leona formation are much smaller and less dependable than that from the Edwards and associated limestones. It is not possible to evaluate quantitatively their potential water resources at this time; however, the geologic map (pl. 1) and records of existing wells can be used as an aid in planning development of supplies from these formations.

The Glen Rose limestone is an important source of water north of the Balcones fault zone in areas where water is not available from the Edwards and associated limestones. The Glen Rose yields sufficient quantities only for domestic and stock supplies and in many places the water is saline. The water of best quality obtained from the Glen Rose comes from wells in which anhydrite beds are not penetrated or have been cased off.

The Buda limestone yields small to moderate supplies of fresh water in its outcrop or where it immediately underlies surficial alluvial deposits. Its potential development is probably greatest in the vicinity of Uvalde; the aquifer becomes less important eastward where it is thinner.

Of the limestone aquifers, the Austin chalk is second in importance to the Edwards and associated limestones. As in the Buda limestone, most of the fresh water is found in the outcrop area where the Austin yields small to large supplies. Large yields at Cline and in an area a few miles southwest of Uvalde suggest that large supplies can be obtained in the western part of the county where the Austin crops out or is close to the surface. Water-level records in a few wells indicate that extended droughts can seriously affect the adequacy of the supply from the Austin.

The potential development of water from the Leona formation is largely dependent upon development of the underlying limestone aquifers. In a large part of the area where the Leona is most productive, it is hydraulically connected with the Buda limestone, Austin chalk, and Edwards and associated limestones. Development from the limestone aquifers may lower the water level, and thus reduce or deplete the supply available from the Leona. The availability of water from the Leona is reduced appreciably by drought also. During the 1947–56 drought, water levels in parts of the Leona River valley declined below the base of the formation, deactivating some of the wells in that area. Other wells in areas where the formation is deeper were productive throughout the drought, despite the lowering of water levels.

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