Report 238

GROUND-WATER AVAILABILITY IN TEXAS

Estimates and Projections Through 2030

EXAS DEPARTMENT OF WATER RESOURCES

September 1979

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SUMMARY OF RESULTS

The average annual ground-water availability from the major and minor aquifers in the State of Texas ranges from approximately 10.2 million acre-feet or 12,600 cubic hectometers (hm^3) in 1980 to 8.4 million acre-feet (10,300 hm^3) in the year 2030. These estimates utilize 5.1 million acre-feet (6,330 hm^3) as annual effective recharge, and the remainder is ground water recoverable from storage in particular aquifers. Current appraisals indicate that approximately 397.6 million acre-feet (453,000 hm^3) is in total storage in these particular aquifers, of which about 327.8 million acre-feet (404,000 hm^3) is considered to be recoverable.

Table 1 shows a breakdown, by aquifer, of the ground-water availability in the State as a whole, and Appendix A gives a detailed tabulation of the availability by aquifer for each river basin or coastal basin, and for each zone. In addition, the condensed description of the principal aquifers and their water-bearing properties in Appendix B may be helpful.

INTRODUCTION

The Importance of Current Ground-Water Availability Knowledge

Texas is fortunate to have ground water as a major natural resource. Even so, heavy pumping of ground water has caused many problems. These problems include land-surface subsidence and greatly increased flood damage potential in the Houston-Galveston area, salt-water encroachment along the Gulf Coast and in the El Paso area, rapid depletion or "mining" of ground-water resources in the High Plains and El Paso area, and substantially increased pumping costs due to falling water tables and decreased well yields. These problems have a noticeable effect on the well-being of Texas cities and industries as well as on State and national agribusiness.

Knowledge of the aquifers in Texas has improved steadily through the collection of additional and more detailed information and through development of more refined methods of appraisal. These improvements, together with the hydrologic changes within some aquifers that have been used for large-scale water production, bring about a need for periodic updating of published information about the availability of ground-water resources. The needs of the State's municipalities, industries, and agriculture will best be met when those involved in managing Texas water resources have the most accurate information available upon which to base their decisions. Good planning is dependent upon reliable ground-water resource estimates and projections.

Purpose and Scope

The purpose of this report is to present information on the quantity of ground water available in the State of Texas on an average annual basis through the year 2030 and thus furnish a comprehensive ground-water reference foundation for future planning efforts at both State and local levels. Specifically, the study provides estimates of the amounts of effective recharge and the amounts of water that can be recovered from storage for selected aquifers in the State. This appraisal re-evaluates and updates the ground-water availability data of the major and minor aquifers as presented in the 1968 Texas Water Plan, and considers additional aquifers where pertinent information has been obtained.

The scope of the study encompassed the collection, compilation, and analysis of data relating to ground-water availability such as: determination of the regional and statewide location and extent of the major and minor aquifers; the available annual effective recharge to each aquifer; computation by best available methods of the amount of ground water in storage that is available for development in selected aquifers; and incorporation of results from using digital mathematic

Table 1.—Summary of Estimated Availability of Ground Water in Texas, by Aquifer, Through the Year 2030

Aquifer	Annual effective recharge (acre-feet/year)	1974 Recoverable storage, (acre-feet)	Projected average annual ground-water availability (annual effective recharge and storage depletion), in acre-feet						Remaining recoverable storage 2031 (acre-feet)
			1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	
Major									
Ogallala	298,200	281,754,000	4,688,000	3,814,800	3,814,800	2,572,200	2,572,200	2,424,800	76,149,600
Carrizo-Wilcox	644,900	12,047,800	847,600	847,600	847,600	847,600	847,600	644,900	0
Edwards (Balcones Fault Zone)	438,700[1]	–	438,700	438,700	438,700	438,700	438,700	438,700	–
Trinity Group	95,100	1,007,900	114,100	114,100	114,100	114,100	114,100	95,100	0
Alluvium and Bolson Deposits	434,000	32,665,500	931,900	974,500	1,017,100	1,084,600	1,152,200	821,300	2,870,000
Gulf Coast	1,229,800[2]	–	1,229,800	1,229,800	1,229,800	1,229,800	1,229,800	1,229,800	–
Edwards-Trinity (Plateau)	776,000	–	776,000	776,000	776,000	776,000	776,000	776,000	–
Minor									
Woodbine	26,100	–	26,100	26,100	26,100	26,100	26,100	26,100	–
Queen City	682,100	–	682,100	682,100	682,100	682,100	682,100	682,100	–
Sparta	163,800	–	163,800	163,800	163,800	163,800	163,800	163,800	–
Edwards-Trinity (High Plains)[3]	–	–	–	–	–	–	–	–	–
Santa Rosa	23,500	–	23,500	23,500	23,500	23,500	23,500	23,500	–
Hickory Sandstone	52,600	–	52,600	52,600	52,600	52,600	52,600	52,600	–
Ellenburger-San Saba	29,400	–	29,400	29,400	29,400	29,400	29,400	29,400	–
Marble Falls Limestone	26,400	–	26,400	26,400	26,400	26,400	26,400	26,400	–
Blaine Gypsum	142,600	–	142,600	142,600	142,600	142,600	142,600	142,600	–
Igneous Rocks	10,700	–	10,700	10,700	10,700	10,700	10,700	10,700	–
Marathon Limestone	18,300	–	18,300	18,300	18,300	18,300	18,300	18,300	–
Bone Spring and Victorio Peak Limestones	17,000	–	17,000	17,000	17,000	17,000	17,000	17,000	–
Capitan Limestone	12,500	375,000	19,400	19,400	19,400	19,400	19,400	12,500	0
Rustler	4,000	–	4,000	4,000	4,000	4,000	4,000	4,000	–
Nacatoch Sand	1,500	–	1,500	1,500	1,500	1,500	1,500	1,500	–
Blossom Sand	700	–	700	700	700	700	700	700	–
Purgatoire-Dakota[3]	–	–	–	–	–	–	–	–	–
Other Undifferentiated (Permian and Pennsylvanian)	2,400	–	2,400	2,400	2,400	2,400	2,400	2,400	–
TOTALS	5,130,300	327,850,200	10,246,600	9,416,000	9,458,600	8,283,500	8,351,100	7,644,200	79,019,600

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[1] The estimate provides for spring flow at San Marcos Springs and protection against water quality deterioration.

[2] The estimate provides for minimum land-surface subsidence.

[3] Included with Ogallala aquifer.

computer models of the Ogallala, Carrizo-Wilcox, Edwards (Balcones Fault Zone), Hueco Bolson, and Gulf Coast aquifers. The computer models have aided and will aid in predicting the effects of ground-water withdrawals on depletion of storage, land-surface subsidence, coastal flooding, salt-water encroachment, and water availability.

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Numerous individuals of the Department's staff assisted in the preparation of this report, therefore, the authors would like to express appreciation to a number of colleagues. Direct supervision and guidance were provided by William B. Klemt, who also prepared portions of and reviewed the report. We are indebted to Robert L. Bluntzer, for his continued support and general direction in this endeavor as well as assistance in several portions of the manuscript, especially those portions concerning the El Paso area. General supervision was furnished by Tommy R. Knowles. Much of the data were reviewed by Richard C. Peckham, a former Ground Water Division director, who prepared the original data for the 1968 Texas Water Plan. We wish to acknowledge the assistance of Department staff members—Loyd Walker and Richard Preston, geologists; Comer Tuck, engineer; and three former staff members—Gunnar Brune, geologist, and Loyd Hamilton and Dick Marshall, hydrologists. Others who assisted the authors were Gerald Adair, Stephen D. Densmore, and former staff members James Krabill and Glen Merschbrock, engineering technicians.

GENERAL HYDROLOGIC PRINCIPLES OF GROUND WATER AND DEFINITION OF TERMS

For the benefit of the general reader, this section is included for familiarization of some basic ground-water hydrologic principles and terms.

Hydrologic Cycle

Water available for use by man—whether as rain, water from wells, or stream discharge—is captured in transit, and after its use and reuse, is returned to the hydrologic cycle from which it came. This cycle is illustrated in Figure 1. Graphically, this figure shows the continuing movement of water from the oceans through evaporation to precipitation and its return, either directly or indirectly, to the ocean. Ground water is part

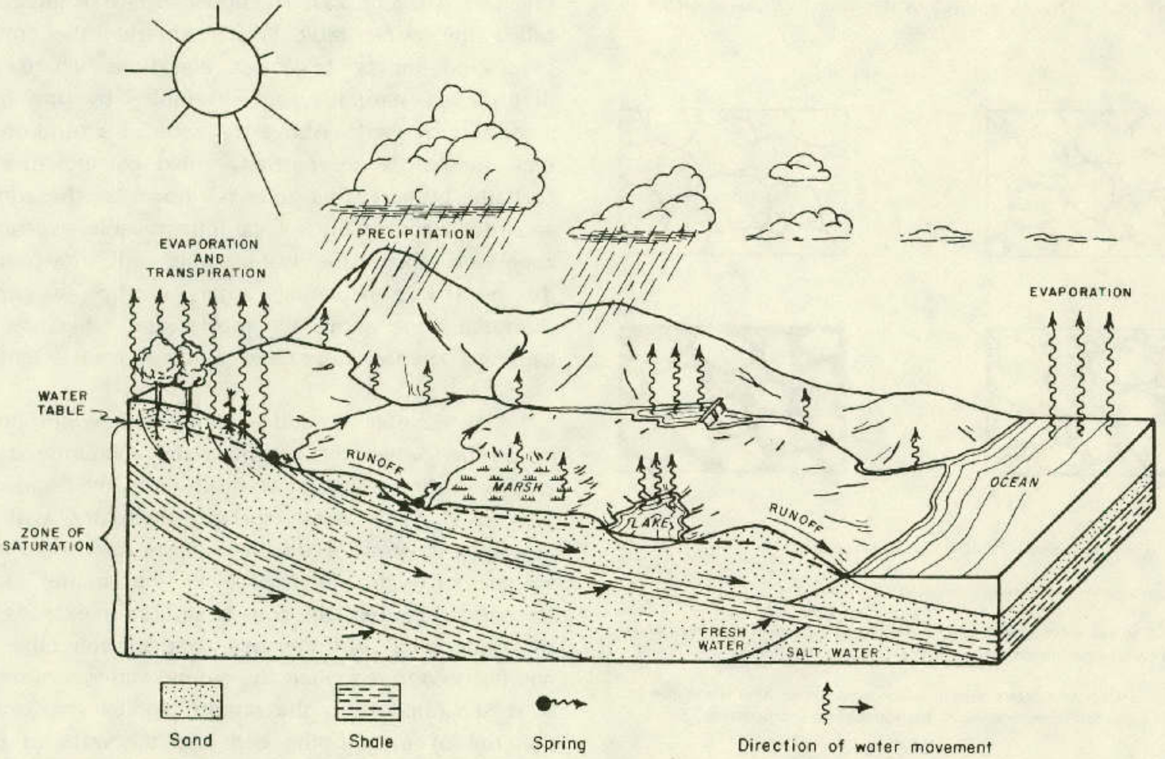


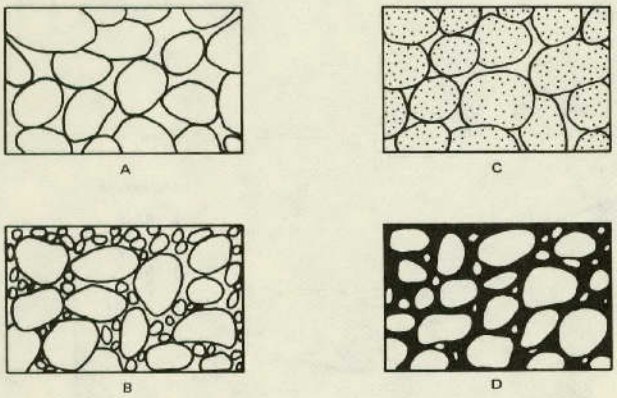
Figure 1.—Hydrologic Cycle

of the returning water which has entered the subsurface and filled the void spaces of the porous rocks which are within the zone of saturation. The primary source of ground water is precipitation, and in general, only a small percentage of the precipitation actually becomes ground water by the process of recharge or effective recharge.

Occurrence

Ground water is contained in the interstices or void spaces of rocks. Two rock characteristics of fundamental importance related to the occurrence of ground water are *porosity,* which is the amount of open space contained in the rock, and *permeability,* the ability of the porous material to allow fluids to move through it. In sedimentary rocks, such as sandstone, gravel, clay, and silt, the porosity is a function of the size, shape, sorting, and degree of cementation of the grains (Figure 2). In limestones, another type of sedimentary rock, the porosity is a function of openings such as cracks, crevices, caverns, and vugs caused in part by dissolution of the limestone by ground water.

Fine-grained sediments, such as clay and silt, usually have high porosity, but due to the small size of the voids, the permeability is low and these formations do not readily yield or transmit water. Therefore, in order for a geologic formation to be an aquifer it must be porous, permeable, and water-bearing. An *aquifer* is made up of sufficient saturated permeable rocks of a geologic formation, group of formations, or part of a formation that is water-bearing (Meinzer, 1923, p. 30). In general, to be an aquifer the water-bearing formation should yield water in sufficient quantities to provide a usable supply; otherwise, the formation may be either an aquitard or aquiclude. An *aquitard* is a semipermeable, semiconfining geologic formation adjacent to or between aquifers and partially restricts the movement of ground water. Clay lenses interbedded with sands are characteristic of "leaky" aquitards. Where the clay is sufficiently thick and widespread, it is usually impervious and the impediment to ground-water movement is greater and confinement of the aquifer is greater; the formation is called an *aquiclude.* Considerable quantities of ground water can be stored in the clay interstices.



A. Well sorted sedimentary deposit having high porosity.

B. Poorly sorted sedimentary deposit having low porosity.

C. Well sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity.

D. Well sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter (cementation) in the interstices.

Figure 2.—Relationship of Rock Texture to Porosity (Adapted from Meinzer, 1923, p. 3.)

When precipitation falls on the outcrop of an aquifer, it may take one of many component courses in completing the hydrologic cycle. A large portion of it returns to the atmosphere by evaporation. Vegetation utilizes a part of it and returns moisture to the atmosphere by transpiration. Some of the precipitation will run off the land surface into streams and return to the sea. A small percentage will percolate downward into formations by the force of gravity to the *zone of saturation* in which the hydrostatic pressure in the water-filled interstices of the permeable rocks of the aquifer is equal to or greater than atmospheric pressure (Meinzer, 1923, p. 21). The upper surface of this zone is called the *water table.* Water entering the zone of saturation moves to lower elevations where it is discharged naturally, for example, by springs or artifically by wells. Above the zone of saturation, the rock interstices are partially filled by moisture and partially by air. This zone is known as the *zone of aeration.* Occasionally a local impermeable layer in this zone and above the water table will intercept the downward percolating water, creating a perched saturated zone above the main water table and thus causing a *perched water table* of limited areal extent.

An aquifer is under *water-table conditions* or *unconfined* when the ground water encountered by a well is in direct contact vertically with the atmosphere (Figure 1). The water surface fluctuates with the atmospheric pressure and in response to changes in the volume of water in storage in the aquifer. In an unconfined aquifer, the zone of saturation extends from the underlying confining bed to the water table. The aquifer is *confined* when the ground water contained in it is separated from the atmosphere by impermeable material of a confining bed and the water is under sufficient pressure to rise above the level at which it is encountered by a well. In this case, the water is under *artesian conditions,* whether it flows at the land surface or not, and the levels to which the water rises in well bores define an imaginary surface called the *piezometric surface.* For a confined aquifer, the zone of saturation represents complete saturation of the water-bearing formation and is equal to its thickness. The term *potentiometric surface* applies both to the piezometric surface of a confined aquifer and the water-table surface of an unconfined aquifer, coinciding with the hydrostatic pressure level of the water in the aquifer (Todd, 1959, p. 29; Lohman, 1972, p. 8).

The *hydraulic gradient* or *pressure gradient* of an aquifer is exemplified by the slope of the potentiometric surface. It is the rate of change of the hydrostatic pressure per unit distance in a given direction. If the rate of change is uniform between two points, the hydraulic gradient between these points is the ratio of the difference in static level between the points to the horizontal distance between them (Meinzer, 1923, p. 38).

The *hydrostatic pressure* is that pressure exerted by the water at any given point in a body of water at rest. That of ground water is generally due to the weight of water at higher levels in the zone of saturation (Meinzer, 1923, p. 37).

The water-producing capability of an aquifer depends upon its ability to store and transmit water. Although the porosity of a rock is a measure of its capacity to store water, not all of this water in storage may be recovered by pumping. Some of the water stored in the interstices is retained because of the molecular attraction between the rock particles and the water. The *coefficient of storage* is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of hydrostatic pressure normal to that surface (Ferris and others, 1962, p. 74). In confined or artesian aquifers, it is the result of two elastic effects—compression of the aquifer and expansion of the contained water—when the hydrostatic pressure is reduced by pumping. The value of the coefficient of storage is small, and it is dimensionless. In the unconfined case, the storage coefficient is also dimensionless and is assumed equal to the specific yield of the material. The *specific yield* measures the water removed from an aquifer by the force of gravity. It has been defined as the ratio of the volume of water which an aquifer, after being saturated, will yield by gravity to the volume of the aquifer drained. The ratio is usually expressed as a percentage (Meinzer, 1923, p. 28).

Recharge, Movement, and Discharge

Recharge is the addition of water to an aquifer and may be absorbed from precipitation, streams, and lakes, either directly into a formation or indirectly by way of another formation. Also, it may mean the quantity of water that is added to the zone of saturation (Meinzer, 1923, p. 46). *Effective recharge* is the amount of water that enters an aquifer and is available for development. Among the factors that influence the amount of recharge received by an aquifer are: the amount and frequency of precipitation; the areal extent of the outcrop or intake area; topography, type and amount of vegetation, and the condition of soil cover in the outcrop area; and the ability of the aquifer to accept recharge and transmit it to areas of discharge.

The quantity of water the aquifer receives as recharge and the ability of the aquifer to transmit water to the areas of discharge are the principal factors that must be considered in determining the amount of water available for withdrawal on a sustained basis. The *coefficient of transmissibility* provides an index of an aquifer's ability to transmit water. It is the amount of water that will flow at a hydraulic gradient or slope of 45 degrees through a vertical strip of the aquifer extending through the full saturated thickness and is expressed as gallons per day per foot, (gal/d)/ft, or as liters per day per meter, (l/d)/m. By using the coefficient of transmissibility, the amount of water that will flow through an aquifer under various hydraulic gradients can be determined. The *coefficient of permeability* is defined as the quantity of water, in gallons per day (gal/d) or liters per day (l/d), that will flow through a section of the aquifer 1 foot square or 1 meter square under a hydraulic gradient of 45 degrees. The coefficient of permeability may be calculated by dividing the coefficient of transmissibility by the thickness of the aquifer.

Ground water moves from the areas of recharge to areas of discharge or from points of higher water level to points of lower water level. Movement is in the direction of the hydraulic gradient just as in the case of surface-water flow. Under normal artesian conditions, movement of ground water usually is in the direction of the aquifer's regional dip. Under water-table conditions, the slope of the water table and consequently the direction of ground-water movement usually is closely related to the slope of the land surface. However, in the case of both artesian and water-table conditions, local anomalies are developed in areas of pumping and some water moves toward the center of artificial discharge.

The rate of ground-water movement in an aquifer is normally very slow, being in the magnitude of a few feet to a few hundred feet per year.

Discharge is the loss of water from an aquifer. The discharge may be either artificial or natural. Artificial discharge takes place from flowing and pumped water wells, drainage ditches, gravel pits, and other excavations that intersect the water table. Natural discharge occurs as effluent seepage, springs, evaporation, transpiration, and interformational leakage (Peckham, 1965, p. 18).

Fluctuations of Water Levels

Changes in water levels indicate a change in the ground-water storage of an aquifer. These changes can be due to many causes, some of regional significance whereas others are confined to more local areas. Basically, water-level fluctuations are caused by changes in recharge and discharge.

When recharge is reduced, as in the case of a drought, some of the water discharged from the aquifer must be withdrawn from storage resulting in a decline of water levels. If water levels are lowered excessively, springs and shallow wells may go dry. However, when sufficient precipitation resumes, the volume of water drained from storage during the drought may be replaced and water levels will rise accordingly. When a water well is pumped, the water level in the vicinity is drawn down to form a shape of an inverted cone with its apex located at the well. This cone of depression in the potentiometric surface is illustrated in Figure 3.

The development or growth of this cone depends on the aquifer's coefficients of transmissibility and storage. As pumping continues, the cone expands until it intercepts a source of replenishment capable of supplying sufficient water to satisfy the pumping demand. This source of replenishment can be either intercepted natural discharge or induced recharge. If the quantity of water received from these sources is adequate to compensate for the water pumped, the growth of the cone will cease and new balances between recharge and discharge are achieved. In areas where recharge or intercepted natural discharge is less than the amount of water pumped by wells, water is removed from storage in the aquifer and water levels will continue to decline.

Where intensive development has taken place in ground-water reservoirs, each well superimposes its cone of depression on the cone of neighboring wells. This results in the development of a regional cone of depression. When the cone of a well overlaps the cone of another, interference occurs and the lowering of water levels is compounded as the wells compete for water by expanding their cones of depression. Figure 4 illustrates the effect of interference between pumping wells. The amount or extent of interference between cones of depression depends on the rate of pumping from each well, the spacing between wells, and the hydraulic characteristics of the aquifer in which the wells are completed.

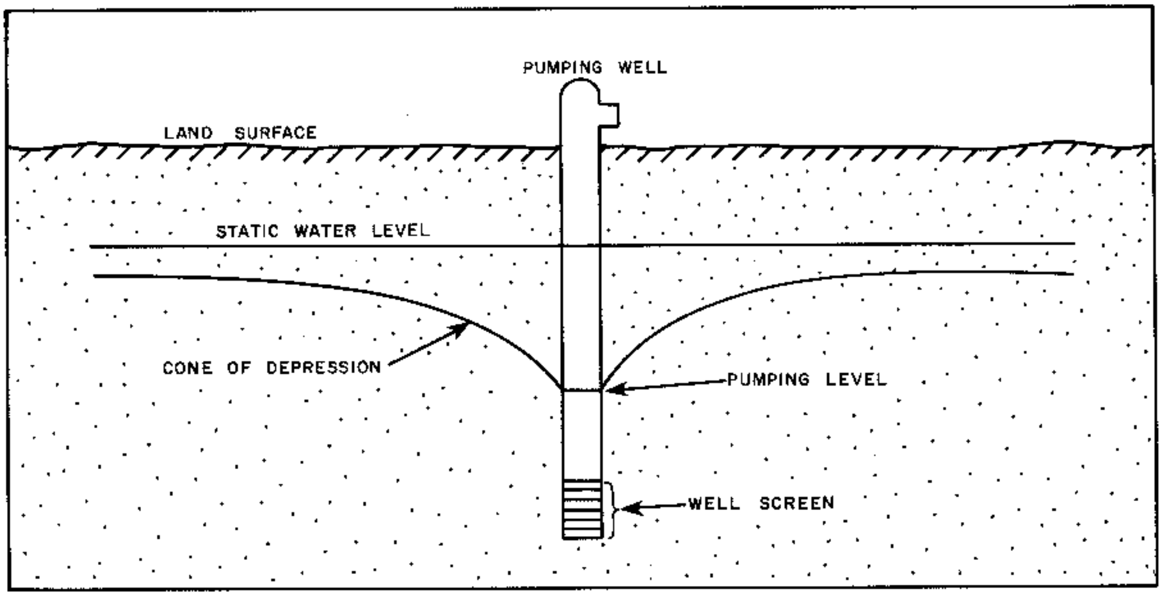


Figure 3.—Cone of Depression Caused by Pumping Well (Taken from Peckham, 1965)

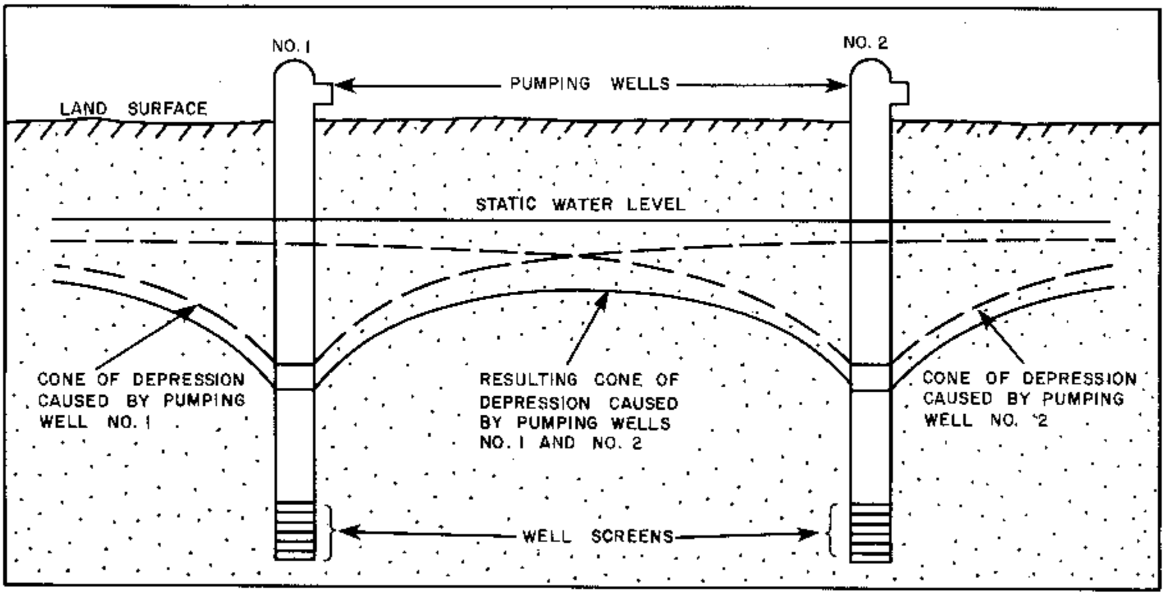


Figure 4.—Effects of Interference Between Two Pumping Wells (Taken from Peckham, 1965)

Additional Terms Defined

Not discussed in the previous section but nevertheless pertinent to this report are terms that necessitate definition.

In the High Plains area of the Texas Panhandle underlain by the Ogallala Formation, the *caprock area* is the upland surface of low relief which occupies the major portion of the area and the *breaks* are considered to be the broken land dissected by ravines along the border of the caprock.

A *leaky aquifer system* is a heteorogeneous assemblage of interrelated permeable, poorly permeable, and relatively impermeable formations that function regionally as an aquifer. The system consists of two or more aquifers separated laterally by discontinuous aquitards and/or aquicludes. Differential changes of the hydrostatic pressure (head) in the system due to pumpage causes ground-water movement through the aquitards and from the interstices of the clays.

Land-surface subsidence is the sinking of the earth's surface due principally to the compression or loading and compaction of fine-grained water-bearing materials (clays) as ground water is released from storage after intensive and prolonged pumping of ground water and, to a lesser degree, hydrocarbons.

Salt-water encroachment can occur when an aquifer, especially a coastal aquifer, has sufficient lateral hydraulic continuity in its water-bearing materials which contain both fresh and saline ground water adjacent to each other, and when the hydrostatic pressure of the saline ground water exceeds that of the fresh ground water. This condition develops when ground-water withdrawals from the fresh-water area of the aquifer reduce the hydrostatic pressure below that of the saline-water area and saline ground water displaces fresh ground water.

In an unconfined aquifer, *total storage* or *underground reservoir capacity,* as used in this report, is the volume of ground water occupying void spaces in the rock which can be recovered by gravity drainage. In a confined aquifer, total storage includes the *artesian (pressure) storage.* Water may be withdrawn from storage at a rate greater than the effective recharge, but only until the water in storage becomes depleted.

Recoverable storage is that portion of underground reservoir capacity estimated as capable of being economically and physically withdrawn from an aquifer.

The estimated *average annual ground-water availability* is the estimated sustainable annual yield, or effective recharge, plus that amount of water which can be recovered from storage over a specified period of time without causing irreversible harm such as land-surface subsidence or water-quality deterioration.

For the purpose of this report, the classification of *ground-water quality* is described as follows:

Fresh—less than 1,000 mg/l (milligrams per liter) dissolved solids

Slightly saline—1,000 to 3,000 mg/l dissolved solids

Moderately saline—3,000 to 10,000 mg/l dissolved solids

Very saline—10,000 to 35,000 mg/l dissolved solids

Brine—more than 35,000 mg/l dissolved solids

Additionally, *well yields* are categorized and are described as follows:

Small—less than 100 gal/min (gallons per minute), or 6.3 l/s (liters per second)

Moderate—100 gal/min (6.3 l/s) to 1,000 gal/min (63 l/s)

Large—more more than 1,000 gal/min (63 l/s)

Conversion From English to Metric Units

The table below gives factors for converting from the English units of measurement employed in this report to the metric equivalents in the International System of Units. This table may be referred to when using any of the tables or appendices. In the text, the metric equivalents have been computed and appear conveniently with each figure expressed in English units.

From English units	Multiply by	To obtain metric units
inches (in)	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
gallons per minute (gal/min)	0.06309	liters per second (l/s)
gallons per day (gal/d)	3.785	liters per day (l/d)
million gallons per day (million gal/d)	3.785	million liters per day (million l/d)
million gallons per day (million gal/d)	0.04381	cubic meters per second (m^3/s)
gallons per day per foot [(gal/d)/ft]	12.418	liters per day per meter [(l/d)/m]
acre-feet	0.001233	cubic hectometer (hm^3)
acres (acres)	0.4047	square hectometer (hm^2)

METHODS OF STUDY AND QUALIFICATIONS

Work began in March 1974 to evaluate the available ground-water supplies which were presented in the 1968 Texas Water Plan. There were four perspectives to the approach: first, to confirm the availability figures given in the 1968 Plan; second, to establish current appraisals where new information had become available from hydrologic studies made since 1968; third, to utilize computer model determinations; and fourth, to incorporate these findings into the State's water planning effort.

In addition, certain factors regarding the evaluation were considered. One factor is that most aquifers extend over broad areas of the State; therefore, when feasible, availability of ground water was computed for the total aquifer. Another factor considered ground-water availability given in terms of storage. These totals were then divided into the various river and coastal basins and zones according to the format established for the "Continuing Water Resources Planning and Development for Texas" document (Texas Water Development Board, 1977).

Next, limits were set on the chemical quality of the ground waters that would be included in the evaluation. Because all aquifers in the State are heterogeneous and anisotropic, the water quality may vary within local areas as well as on a regional basis. Such conditions can impose restrictions on the development and utilization of the ground water since it may not be suitable for a specific purpose; for example, municipal, industrial, agricultural, and domestic uses. Ground water could have an extremely high iron or silica content and not be suitable for industrial use. Water containing high sulfate may have a laxative effect when consumed by humans and animals. A high boron content can be harmful to the growth of certain irrigated crops. Also, current U.S. Environmental Protection Agency standards and the modified Texas Department of Health standards may further impose restrictions on municipal use of certain waters. (Texas Department of Health, 1977.)

In general, only the quantity of fresh to slightly saline ground water, containing less than 3,000 milligrams per liter (mg/l) dissolved solids, was evaluated. Exceptions were made for the Blaine Gypsum, Santa Rosa, and Rustler aquifers where moderately saline ground water (3,000 to 10,000 mg/l) was included for irrigation purposes.

The average annual ground-water availability of an aquifer is that amount of water which can be developed throughout its extent and is comprised of the annual effective recharge plus the amount of water that can be recovered annually from storage over a specified planning period without causing irreversible harm such as land-surface subsidence or water-quality deterioration (Appendix A). One well or a local well field cannot recover the total amount of ground water available from an aquifer. Also, since all aquifers in the State are heterogeneous and anisotropic, water wells can have a wide range of production within very local areas and on a regional basis.

When considering the development of a new ground-water supply or the enhancement of an existing supply, the developer should analyze the quantity and quality of the ground water available in the area under study. Particular attention should be given to the amount of ground water which can be withdrawn without having adverse effects on water levels and water quality. Also, other existing or future ground-water developments in the study area which may adversely affect a new water supply should be evaluated. The analyses of the ground-water availability in this report are based upon the assumption that the water developer will use the proper methods and procedures to locate, space, construct, and complete water wells in order to maintain maximum well efficiency by preventing "sanding up" of well screens and pumps and, more importantly, to minimize degradation of ground-water quality caused by leakage along the borehole and by saline-water encroachment.

Procedural steps used to appraise the ground-water availability of an aquifer were to review and utilize pertinent publications and then select an evaluation method or combination of methods to derive the average annual ground-water availability. These methods generally fell into four basic definitive hydrologic groups, namely (1) steady-state flow under the supposition that water levels did not change with time and natural recharge balanced discharge; (2) nonsteady-state flow under water table and nonleaky and leaky artesian conditions; (3) circumstances requiring geohydrologic judgments that placed limitations on development of certain aquifers owing to their susceptibility to ground-water quality degradation, land-surface subsidence, and other characteristics unique to the aquifer; and (4) systematic depletion of ground water that is recoverable from storage. A discussion of methodologies developed to appraise the amounts of ground water available in Texas follows, and additional specific application of these methods to each aquifer can be found in more detail in the major and minor aquifers sections of this report.

Steady-State Flow Methods

Although it is recognized that steady-state flow does not generally happen in nature, the concept that it is approximated in nature is beneficial to the development of analytical methods used to evaluate the available ground water in an aquifer. If so, the discovery by Henri Darcy in 1856 that the rate of water flowing through sand is proportional to the hydraulic gradient is applicable here (Lohman, 1972, p. 10). This relation is known as Darcy's law, and Bennett (1976, p. 14) states that it "relates specific discharge, or discharge per unit area, to the gradient of hydraulic head. It is the fundamental relation governing steady-state flow in porous media." Darcy's law may be expressed by the equation:

$$q = Q/A = -K\, dh/dl,$$

where q is the specific discharge per unit area, Q is the rate of discharge or flow, A is the cross-sectional area through which the discharge or flow passes and is normal to the direction of flow, K is the hydraulic conductivity or permeability of the porous medium, and dh/dl is the head gradient or hydraulic gradient.

In deriving the various methods under steady-state flow, the fundamental relation of Darcy's law was assumed. Values for the parameters of discharge, Q; applicable area, A; permeability, K; and the hydraulic gradient, dh/dl were obtained by the best procedures depending on the form of the available data such as spring flow, base flow, mean annual precipitation, and water level. The methods used under steady-state flow are (1) base-flow and spring-flow measurements, (2) low-flow and flow-net analysis, (3) the trough method, (4) the comparison of pumpage data and water-level trends, and (5) the use of a percentage of the mean annual precipitation upon the aquifer outcrop as effective recharge.

Base-Flow and Spring-Flow Measurements

The ground-water availability of an aquifer was determined by the base-flow and spring-flow measurements method in terms of the annual effective recharge rate when the hydrological information was available (Brune, 1975, p. 3-4; Reeves and Small, 1973, p. 28). The conceptual representation is that inflow (recharge) equals outflow (discharge)—a condition of steady flow, and for any given aquifer with a suitable geohydrological orientation, the stream base flow and spring flow may be used to determine these quantities. In addition, the components of pumpage from the aquifer and water losses, such as evaporation along the streams and transpiration by crops and phreatophytes, must be included as outflow. It follows that the quantity found for the annual effective recharge may be applied to the aquifer outcrop area to determine the percentage of the mean annual precipitation that becomes recharge. Subsequently, this percentage factor may be projected to nearby aquifer outcrop areas where data are lacking provided that the geohydrological conditions are similar. This method was used in varying degrees to find the amount of ground water available as annual effective recharge from the alluvium, Edwards (Balcones Fault Zone), Marble Falls Limestone, Edwards-Trinity (Plateau), Ellenburger-San Saba, Trinity Group, Capitan Limestone, and Rustler aquifers.

Low-Flow and Flow-Net Analysis

When conditions of an aquifer and an associated stream regimen are stable, such as during the winter months when evapotranspiration and pumpage are negligible, the low-flow and flow-net analysis method may be used to find the effective recharge (Walton, 1962, p. 14, 15, 52, and 53). The discharge from an aquifer can be determined by measuring the low flow between two points along a streambed and finding the potentiometric surface discharge area on both sides of the stream contributing to that segment. This water-table discharge area may be delineated by constructing hydraulic gradient flow lines normal to the contours on the potentiometric surface. The increased flow along the stream segment amounts to the discharge from the aquifer and, when applied to the contributing area, is the estimated effective recharge. When one performs the same analysis on several areas, then the accuracy of the estimate is increased. The resultant percentage of the mean annual precipitation may then be projected over the whole aquifer and the total effective recharge determined. This method was used for the Alluvium (Seymour Formation) of north central Texas.

Trough Method

The so-called trough method is a geometric application of Darcy's law and is used to evaluate the annual effective recharge available from an artesian or confined aquifer (Klemt and others, 1975, p. 11-12). With constraints imposed by the economic feasibility of pumping lifts, the trough method assumes the lowering of water levels to the top of the aquifer downdip from the outcrop to a maximum of 400 feet (122 m) below the land surface. Exception was made for the Gulf Coast aquifer where constraints were used to minimize land-surface subsidence and saline-water encroachment. Here, water levels were lowered a maximum of 150 feet (46 m) below the land surface along a line approximately midway between the outcrop and the downdip interface between the fresh and moderately saline water. The quantity of water that the aquifer will transmit under the hydraulic gradients established between the recharge area and the innumerable points of discharge along an approximate line of discharge provides an index to the aquifer's maximum effective recharge capability if the water is available in the outcrop. The reliability of the percentage of the mean annual precipitation as effective recharge used for artesian aquifers can be verified by the trough method (Peckham and others, 1963, p. 57-59), and the two methods should be used together when possible. The ground-water availability was determined in whole or in part using this method for the Woodbine, Trinity Group, Carrizo-Wilcox, Sparta, Queen City, and Gulf Coast aquifers.

Comparison of Pumpage Data and Water-Level Trends

Evaluation of an aquifer's effective recharge by this method involves measuring the change in storage in the aquifer or reservoir caused by the influences of inflow and outflow (Keech and Dreezen, 1959, p.44-48; Shamburger, 1967, p. 66-68). If there is no net change in storage, then a steady-state flow analysis applies. More simply, change in storage equals inflow minus outflow. The components of inflow may include natural recharge derived from precipitation, infiltration of irrigation water returning to the aquifer, influent streamflow, and possible subsurface inflow; and the components of outflow may include pumpage, effluent streamflow, evapotranspiration, and possible subsurface outflow. Historical data for these factors with respect to both completeness and length of record are important to the accuracy of the appraisal. Usually, information is available for the precipitation, pumpage, and water levels. Reasonable estimates derived from other hydrologic studies must be made for the remaining components.

This method is best exemplified in the case of the Leona Alluvium in Tom Green County where the effective recharge was evaluated by the following analysis. First, the effective recharge area of the aquifer was determined from a geologic map using a grid spatial count. Second, the City of San Angelo historical precipitation record from 1940 to 1975 was plotted on a graph. The historical water-level measurements for a comparable period from two representative wells within the aquifer area were plotted on the same graph. The ground-water pumpage was plotted for the years 1958, 1964, 1969, and 1974, and the surface-water diversions from Twin Buttes Reservoir to the aquifer recharge area were plotted for the years 1972, 1973, 1974, and 1975. Third, the control period from 1961 to 1975 was selected for the analysis because the water levels were at their highest points and approximately equal at the beginning and end of this interval—no net change in ground-water storage. Fourth, the effective recharge was calculated by using the average pumpage during the control period and subtracting 20 percent of the Twin Buttes Reservoir surface-water diversions for irrigation as infiltration returning to the Leona Alluvium. In this analysis, the influence of the Concho River was considered to be inconsequential, the effects of subsurface inflow and outflow were assumed negligible, and evapotranspiration was incorporated into the estimated 20 percent of surface-water diversions that become ground-water recharge. The resultant effective recharge was calculated to be approximately 4.6 percent of the mean annual precipitation between 1961 and 1975 on the effective recharge area.

Besides the Leona Alluvium, other aquifers for which this method or a similar method were used are the Santa Rosa, Cenozoic Alluvium of West Texas, Brazos River Alluvium, Edwards (Balcones Fault Zone), Bone Spring and Victorio Peak Limestones, and some of the other undifferentiated aquifers.

Use of a Percentage of the Mean Annual Precipitation Upon the Aquifer Outcrop as Effective Recharge

Using this method to determine ground-water availability first requires finding the total amount of recharge area. This was accomplished by using a geologic map to measure the outcrop area with a planimeter or grid spatial count. Next, an estimate of the percentage of the mean annual precipitation falling on this area that becomes effective recharge was derived from data in pertinent publications and indirectly through steady-state flow analyses from base-flow studies, low-flow measurements, and spring-discharge data. Mean annual precipitation data used were based on historical rainfall records. In the case of artesian (confined) aquifers, the effective recharge factor was validated and possibly limited by checking the aquifer's transmission capacity with the trough method (Peckham and others, 1963, p. 57-59).

The ground-water availability was determined in whole or in part by this method in the following aquifers: the Alluvium and Bolson Deposits, Blaine Gypsum, Nacatoch Sand, Blossom Sand, Woodbine, Trinity Group, Hickory Sandstone, Carrizo-Wilcox, Igneous Rocks, and Marathon Limestone.

Nonsteady-State Flow Methods

Bascially, nonsteady-state flow differs from steady-state flow in that the water levels decline as a result of withdrawals or discharge from an aquifer. As a consequence, ground water is taken from storage. In the analysis of nonleaky and leaky artesian conditions, the coefficients of storage are assumed constant and ground water is released from storage instantaneously. Under water-table conditions, ground water is released from storage by gravity drainage. As the discharge proceeds through a long time period, the effects of gravity drainage become negligible and the water-table conditions approximate nonleaky artesian conditions in that the coefficient of storage approaches constancy (Walton, 1962, p. 6). With this understanding of nonsteady-state flow in mind, the authors utilized the results of water-budget studies and computer modeling techniques where nonsteady-state flow methods were applicable.

Water-Budget Studies

Water-budget studies entail the comprehensive use of all or some of the previously described methods for deriving the average annual ground-water availability. In essence, it is the balancing of the hydrologic equation and may be stated as inflow equals outflow plus or minus change in ground-water storage. Inflow may include precipitation, surface streamflow, import water, and water derived from clays due to subsidence. Outflow may include consumptive use (pumpage and evapotranspiration), surface streamflow, export water, and subsurface outflow. Using applicable parameters from the above hydrologic relationship, it is possible to determine the specific yield of an aquifer (Cenozoic Alluvium of West Texas) by comparing historical pumpage records with the total volume of the dewatered portion of the aquifer (Walton, 1962; Lohman, 1972). Another prime example of a water-budget study is the one conducted on the Lower Mesilla Valley and El Paso Valley (Meyer and Gordon, 1973).

Computer Modeling

Computer modeling utilizes many of the previously described methodologies. The procedure characteristic to each aquifer model will be discussed in sections dealing with the individual aquifers for which digital computer modeling techniques were used to determine the average annual ground-water availability. These include the Hueco Bolson, Ogallala, Gulf Coast, Carrizo-Wilcox, Trinity Group, and Edwards (Balcones Fault Zone) aquifers. An overview of the computer model principles used for these aquifers is presented here (Klemt, Perkins, and Alvarez, 1975; Klemt, Duffin, and Elder, 1976; Klemt and others, 1979; Prickett and Lonnquist, 1971.

The ability of the digital computer to solve sets of simultaneous differential equations quickly provides a means to simulate aquifer systems. In the case of the above aquifers, except for the Ogallala, the digital model is based on the differential equation for a two-dimensional nonsteady flow system of a compressible fluid in an elastic, heterogeneous, porous medium and may be expressed by the following equation:

$$\partial/\partial x(T\partial h/\partial x) + \partial/\partial y\ (T\partial h/\partial y) = S\partial h/\partial t + W\ (x, y, t),$$

where T is the transmissibility tensor (L^2/T), h is the hydraulic head (L), S is the storage coefficient (dimensionless), t is time (T), W is the volume flux per unit area (L/T), and x,y are rectangular coordinates (L). The dimensions are distance (L) and time (T).

The numerical solution of the above equation can be approximated with a finite difference approach which consists of (a) superimposing a finite difference grid upon a map delineating the extent of the aquifer and dividing it into cells with nodes at the centers; (b) using finite difference approximations of the above equation to formulate a set of equations for ground-water flow for each element or cell in the discretized model; and (c) solving this set of equations with the digital computer for the hydraulic head using the iterative alternating-direction implicit procedure. This procedure is a mathematical process which reduces a system of simultaneous equations to a number of smaller sets for a given time interval. When all equations have been solved, one iteration is completed. The iteration process is repeated until the sum of the changes in hydraulic head for the iteration is less than the prescribed error tolerance for the desired time period. Values of various hydrologic parameters are assigned to each node in the digital model. These values are for the transmissibility, storage coefficient, land-surface elevation, initial head, elevations at top and base of the aquifer, node dimensions, and recharge and pumpage rates. When applicable, the values of these parameters may be varied to meet simulation objectives and thus evaluate the average annual ground-water availability.

Circumstances Requiring Geohydrological Judgments

In applying the above methodologies for determining ground-water availability, it was necessary to make certain judgments concerning the particular geohydrological conditions of each aquifer. Some of these assumptions have been mentioned and will become more explicit in the individual aquifer discussions of this report; however, four are mentioned here as examples. First, the projections of a percentage of the mean annual precipitation as annual effective recharge over outcrop areas, where the actual evaluation of recharge was not made, required a judgment as to the geohydrological similarity between the areas. Second, the ground water available from the Blaine Gypsum aquifer was calculated only for areas in the Red River basin even though the aquifer extends southward to Tom Green County. This was done because the Blaine Gypsum was judged less productive and the ground water is of poor quality outside the Red River basin. Third, it was estimated that only 30 percent of the total quantity of fresh ground water in storage in the Cenozoic Alluvium aquifer in Winkler and Ward Counties could be developed without rapid degradation of water quality caused by the migration of undesirable water. This amount of development would minimize water-level declines and steep hydraulic gradients. Fourth, based on economic factors, it was assumed that all drainable water except that in the deepest 20 feet (6 m) of saturated thickness in the Ogallala aquifer could be withdrawn from storage. The transmissibility of the remaining 20 feet (6 m) of saturated thickness should be approximately 10,000 (gal/d)/ft, or 124,000 (l/d)/m, which would be enough to support well yields of about 50 to 75 gal/min (3.2 to 4.7 l/s). High permeabilities in the Leona Alluvium aquifer allowed for less than 20 feet (6 m) of saturated thickness remaining and would still maintain a transmissibility of 10,000 (gal/d)/ft or 124,000 (l/d)/m. Furthermore, when it was not possible to find the remaining saturated thickness by the above procedure, then it was estimated that all except 25 percent of the total storage could be recovered. Following the determination of the amount of water-saturated thickness that will remain, the amount of recoverable ground water in storage could be computed.

Systematic Depletion of Ground Water That Is Recoverable From Storage

The methodology used to determine the depletion rate of ground water recoverable from storage differs for artesian (confined) aquifers, water-table (unconfined) aquifers, and those aquifers with certain pumpage constraints imposed to prevent the degradation of ground-water quality.

In the case of artesian aquifers, the amount of artesian storage proposed for development was determined by theoretically lowering the water level with innumerable discharge points lying in the area between the aquifer outcrop and the downdip limit of the fresh to slightly saline water, or bad water line (Figure 5). With due consideration given to the transmission capacity of the aquifers and to pumping lift costs, the theoretical lowering of the hydraulic heads or water levels in central and east Texas was limited to a maximum of 400 feet (122 m) below the land surface for the Carrizo-Wilcox aquifer and to a maximum level of 100 feet (30.5 m) above the top of the Trinity Group aquifer.

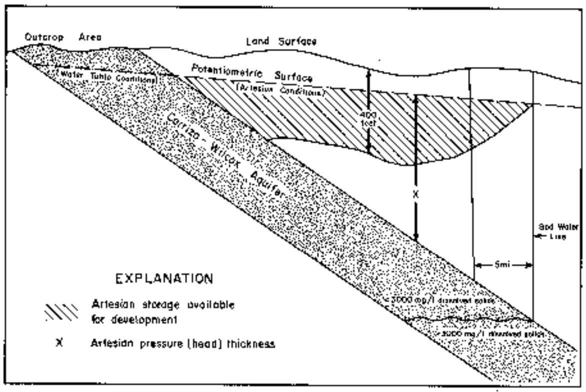
For water-table aquifers, a first step in determining the amount of water recoverable from storage is finding the minimum remaining saturated thickness in the aquifer that would maintain a transmissibility of 10,000 (gal/d)/ft, or 124,000 (l/d)/m, which is considered to be the least value for which large-capacity well operations would be economically feasible. The minimum remaining saturated thickness was determined by using the available well data in the effective aquifer area such as well depths, static water levels, pumping water levels, and yields. From this information, the remaining saturated thickness was computed with the following formulas:

$T = 1460\ Q/Sw$ (Modified Thiem Formula),

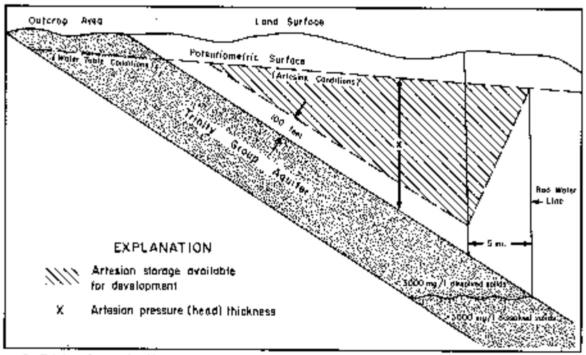
$P = T6/m$, and

$m_R = 10{,}000/P$;

where T is transmissibility in (gal/d)/ft, 1460 is the factor applicable to water-table conditions, Q is well yield in gal/min, Sw is drawdown in feet, P is permeability in (gal/d)/ft^2, m is saturated thickness in feet, m_R is remaining saturated thickness in feet, and 10,000 is the minimum transmissibility required for economical large-capacity well operations in (gal/d)/ft.



A. Carrizo-Wilcox Aquifer



B. Trinity Group Aquifer

Figure 5.—Diagrammatic Cross-Section Through Confined Aquifers Showing Depletable Artesian Ground-Water Storage

The recoverable water that can be withdrawn from storage was found by (a) constructing a saturated thickness map of the effective aquifer area, (b) constructing a minimum remaining saturated thickness map, (c) superposing these maps and constructing a "depletion" saturated thickness map, and (d) finding the quantity of water recoverable from storage by computing the total storage volume in the depletion zone and multiplying it by the coefficient of storage. Obviously, the quantity of water in storage in the aquifers of the State can be withdrawn at a wide range of annual rates which can be varied from year to year. In view of these possibilities and in view of the fact that it is not possible to predict these annual rates with a high degree of certainty, a baseline computation of the estimated withdrawal of ground water from storage was made for each aquifer. This was based on the assumption that the planning horizon for the use of these waters is the period 1977 to 2030. In most instances, the annual storage depletion rate was calculated by dividing the recoverable storage by 53 years which is the depletable or planning period to the year 2030 (Texas Water Development Board, 1977, p. II-65). This depletion rate was then added to the estimated annual effective recharge to give the estimated average annual ground-water availability as shown, by decade, in Appendix A for the time period 1980 to 2030.

The minimum remaining saturated thickness for the Ogallala aquifer which would still maintain a transmissibility of 10,000 (gal/d)/ft, or 124,000 (l/d)/m, was estimated to be 20 feet (6 m). For the Cenozoic Alluvium aquifer, the available water recoverable from storage was limited by constraints imposed to prevent the degradation of ground-water quality. When information was lacking to calculate the minimum saturated thickness by the above described method, 75 percent of the total water in storage was estimated to be recoverable. Depletion of ground water from storage was also appraised for all of the Bolson Deposits, Brazos River Alluvium, Alluvium (Seymour Formation), Trinity Group, and Carrizo-Wilcox aquifers.

For many of the aquifers, the record of pumpage reveals that in certain local areas the withdrawal of water from storage exceeds the estimated annual recharge and, in addition, exceeds the rate of withdrawal at which the water in recoverable storage would last to the year 2030 (Appendix A). Explicitly, ground-water mining is occurring at various rates within some areas of Texas, and in order to continue the water using economic activities of these areas, alternate water supplies must be developed. Thus, these data will be useful for planning and developing future water supplies.

GENERAL DISTRIBUTION OF THE AQUIFERS, THEIR WATER-BEARING PROPERTIES, AND THE AMOUNTS OF WATER AVAILABLE

Major Aquifers

A major aquifer is defined as one which yields large quantities of water in a comparatively large area of the State. The major aquifers in this report are essentially the same as those described in the 1968 Texas Water Plan. The location and extent of the aquifers are shown on Figure 6 and their ground-water availability is given in Table 1 and Appendix A. Water-bearing properties of the major aquifers are described in Appendix B. A description of the major aquifers and the availability of ground water from them follows.

Ogallala

The Ogallala Formation of Pliocene age is the major aquifer on the High Plains of northwest Texas. It reaches a maximum known thickness of almost 900 feet (274 m) in southwestern Ochiltree County. The Ogallala is composed of unconsolidated, fine- to coarse-grained, gray to red sand, clay, and silt. In places, it contains some quartz gravel and caliche.

Water-bearing areas of the Ogallala are hydraulically connected except where the Canadian River has eroded partially or totally through the formation. In this region, the river has separated the High Plains proper into two areas. The northern part is referred to as the North Plains and the southern segment is known as the South Plains.

The saturated thickness of the Ogallala Formation ranges from a few feet to more than 525 feet (160 m) in south-central Ochiltree County. In general, the areas with greatest saturated thickness lie in the North Plains. South of Lubbock to Midland County, the saturated zone varies from less than 50 feet (15 m) to 200 feet (61 m).

Depth to water below the land surface reaches almost 400 feet (122 m) in parts of the North Plains, but ranges from 100 to 200 feet (30 to 61 m) throughout much of the South Plains. Yields of wells vary from less than 100 gal/min (6.3 l/s) to more than 2,000 gal/min (130 l/s). The average yield is approximately 500 gal/min (32 l/s).

Ground water moves slowly through the Ogallala Formation in a generally southeastward direction toward the caprock edge or eastern escarpment of the High Plains. Its limited effective recharge is derived from precipitation on the land surface and by underflow from New Mexico. The recharge from precipitation is severely impeded by relatively impervious clay layers and caliche which overlie much of the formation.

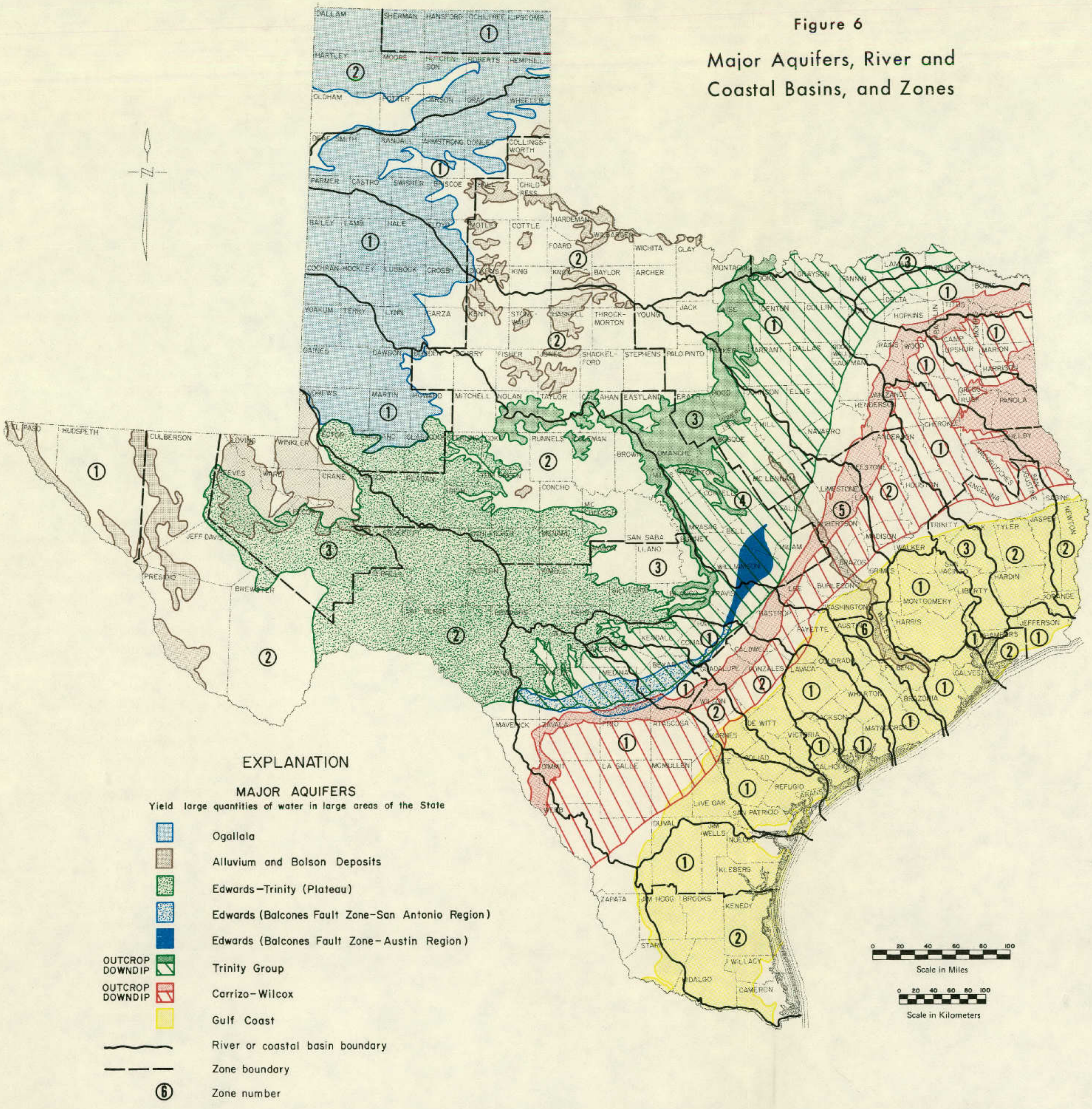
The Ogallala ground water is generally fresh. It usually contains between 300 and 1,000 mg/l of dissolved solids of which calcium, magnesium, and bicarbonate are the principal constituents. The water is hard. Widely distributed small areas of ground water containing relatively high chloride concentrations occur mainly near large saline playa lakes and in the southeastern part of the South Plains where the water table is shallow.

Ground water available for development from the Ogallala aquifer is expressed in terms of average annual ground-water availability (Table 1 and Appendix A). These quantities represent the annual effective recharge to the aquifer plus depletion from recoverable storage. Computer modeling techniques were used to estimate the total ground water in storage (Wyatt, 1975).

Development of a computer model for the Ogallala aquifer required the use of historical data from selected

Figure 6

Major Aquifers, River and Coastal Basins, and Zones



water wells, historical water-use information, and the consideration of a diminishing saturated thickness and its effect on well yields. With the above parameters incorporated into the system, the primary objective of the computer model was to calculate future saturated thickness and the total volume of ground water in storage.

This objective was accomplished with a county-by-county approach utilizing the available data (Wyatt and others, 1976). Water wells were selected within each county for control if each had an adequate historical water-level record, penetrated the complete thickness of the aquifer, and fulfilled distribution requirements. In some cases, imaginary wells were designated to fulfill distribution requirements. Water-use patterns between 1960 and 1972 were compared to water-level changes in the control wells for the same period. It was determined that the rates of water-level decline and water use directly correlate to aquifer saturated thickness, that is, greater rates of decline resulted when the saturated thickness was greater and the reverse was true for lesser saturated thicknesses. This analysis resulted in the development of a depletion schedule for the period between 1960 and 1972 which was incorporated into a computer model of the Ogallala aquifer. Wyatt and others (1976, p. 5 and 6) provide example calculations showing the procedures followed to estimate future saturated thickness from the depletion schedule. The total volume of ground water in storage in the Ogallala aquifer at prescribed time intervals was thus computed using a coefficient of storage or specific yield of 0.15 (Wyatt, 1975).

That portion of the total volume of ground water in storage which can be recovered was determined by assuming that all except that in the last 20 feet (6 m) of saturated thickness can be withdrawn from the aquifer in view of current economic and technical development standards. Based on the water-use patterns, water-level declines in the control wells, and the resultant depletion schedules developed for the known historical period 1960 to 1972, the available recoverable storage, by decade, was determined by the computer analysis to the year 2020. The depletion rate between 2010 and 2019 was used to project depletion of recoverable storage from 2020 to 2029 and during 2030, provided that sufficient quantities of water were available in recoverable storage. Otherwise, the water in recoverable storage becomes exhausted during the applicable period. Furthermore, when the saturated thickness of the Ogallala becomes depleted to approximately 20 feet (6 m) remaining, yields from wells will probably be reduced to a point of near equilibrium such that withdrawals will approximately equal the aggregate of effective recharge, irrigation return flows, and possible lateral inflows from adjacent areas. The transmissibility of the remaining 20 feet (6 m) of saturated thickness should be approximately 10,000 (gal/d)/ft, or 124,000 (l/d)/m, which should be adequate to support well yields of about 50 to 75 gal/min (3.2 to 4.7 l/s).

The effective recharge to the aquifer was assumed to be 0.175 inch (0.445 cm) per year (Theis, 1937). The volume of water recharged was determined by multiplying this annual rate by the outcrop area within each county. Total annual effective recharge equals 298,200 acre-feet or 367 hm^3 (Table 1 and Appendix A).

Based on the Ogallala digital computer model, the estimated total amount of ground water in storage in the Ogallala aquifer in 1974 was approximately 340 million acre-feet (419,000 hm^3), of which about 266 million acre-feet (328,000 hm^3) or 78 percent was in the High Plains proper or upland areas and about 74 million acre-feet (91,000 hm^3) or 22 percent was in the "breaks" or broken land dissected by ravines along the border of the caprock. Of the total quantity of water in storage, about 282 million acre-feet (348,000 hm^3) is considered to be recoverable with about 218 million acre-feet (269,000 hm^3), or 77 percent, coming from the High Plains proper and approximately 64 million acre-feet (79,000 hm^3), or 23 percent, from the "breaks" area.

Included in the above ground-water availability figures for the Ogallala is water available from the Edwards-Trinity (High Plains) and Purgatoire-Dakota aquifers which immediately underlie the Ogallala in certain areas. These are discussed in a later section of this report on minor aquifers.

Carrizo-Wilcox

The Carrizo-Wilcox aquifer of Eocene age is one of the most extensive aquifers in Texas, furnishing water to wells in a wide belt extending from the Rio Grande northeastward into Arkansas and Louisiana (Figure 6). The aquifer consists, for the most part, of hydrologically connected ferruginous, cross-bedded sand with clay, sandstone, silt, lignite, and gravel of the Wilcox Group and overlying Carrizo Formation (Peckham and others, 1968).

The Carrizo-Wilcox aquifer is recharged by precipitation and by streams crossing the outcrop area. The Wilcox Group and Carrizo Formation dip beneath the land surface toward the Gulf except in the East Texas structural basin adjacent to the Sabine Uplift where the formations form a trough. In addition, the formations are exposed at the surface in the uplift area where the dip is away from the structural high. The thickness of the aquifer in the downdip, artesian areas ranges from 150 feet (46 m) in Dimmit County to more than 3,000 feet (914 m) in Atascosa County.

Yields of wells vary widely. They are commonly 500 gal/min (32 l/s), and may reach 3,000 gal/min (190 l/s) downdip from the outcrop where the aquifer is under artesian conditions. These yields permit large annual withdrawals of ground water from storage (mining) and in many cases have caused pronounced declines of water levels, particularly in the Winter Garden District (Dimmit and Zavala Counties) and in the municipal and industrial well fields north of Lufkin in Angelina and Nacogdoches Counties.

Reduction of artesian pressure is causing leakage between beds and encroachment of poorer quality water into the Carrizo-Wilcox. In local areas, especially in Dimmit County, saline water from the overlying Bigford Formation is leaking through old well bores and contaminating the aquifer. When these wells were drilled in the 1920's and 1930's, water levels in the Carrizo-Wilcox aquifer were considerably above the water levels in the saline-water sands of the Bigford. Because of excessive pumpage, the water levels of the Carrizo-Wilcox have been significantly lowered below the levels of the Bigford saline water sands. Since the old wells were poorly constructed initially and may not have been properly plugged and sealed, the saline water moves down the boreholes and mixes with the Carrizo-Wilcox water, thus degrading its quality. Furthermore, excessive pumpage in certain areas is causing reversals of the hydraulic gradient in the aquifer, thus inducing a shift in the aquifer's "bad water line" which results in encroachment of poorer quality water into areas previously having better quality water.

Throughout most of its extent in Texas, the Carrizo-Wilcox aquifer yields fresh to slightly saline water which is acceptable for most irrigation, public supply, and industrial purposes. In the outcrop area, the aquifer contains hard water yet is usually low in dissolved solids content. Downdip, the water is softer, has a higher temperature, and contains more dissolved solids. Hydrogen sulfide and methane gas may occur locally. Excessively corrosive water with a high iron content is common throughout much of the northeastern part of the aquifer.

Rio Grande, Guadalupe, San Antonio, and Nueces River Basins

In 1967, as part of the regional study of the Guadalupe, San Antonio, and Nueces River basins, a comprehensive investigation of the Carrizo-Wilcox aquifer was initiated. The principle objective of the study was to obtain reliable geohydrologic data to evaluate the long-term regional water supply capability of the Carrizo aquifer in South Texas.

A technique developed was a computerized mathematical representation or digital computer model (Klemt and others, 1976). The purpose of the model was to simulate the response of water levels in the Carrizo aquifer to pumpage and recharge for any given time period. This simulation process provided a means for determining the ability of the Carrizo aquifer to meet anticipated pumpage. Also, model application delineated areas having various degrees of favorability for future ground-water development from the aquifer.

The model was verified using historical recharge and pumpage data for the period 1963 through 1969. The computed water levels when compared to historically observed water levels for this period had an average error of -0.53 foot (-0.16 m). More than 90 percent of the simulated water levels for 1969 were within ± 25 feet (7.6 m) of historical water levels. The majority of the simulated data not meeting this criteria was in the extreme downdip portion of the aquifer where the availability of reliable historical water-level data was very limited.

The average annual ground-water availability of the Carrizo-Wilcox was determined in the Rio Grande, Guadalupe, San Antonio, and Nueces River basins by the use of the Carrizo aquifer model. A percentage of the average annual rainfall was applied as effective recharge to the outcrop area of the Wilcox and a small portion of the Carrizo outcrop outside of the model area. The average annual ground-water availability of the Carrizo-Wilcox aquifer is defined as the ground-water withdrawals which can be developed annually until the year 2030 without causing (a) a decline in water levels of more than 400 feet (122 m) below land surface or (b) a decline in water levels below the top of the water-bearing sands.

The average annual ground-water availability of the aquifer includes both the aquifer's effective recharge and water removable from storage between 1977 and the year 2030 under the assumption that water in storage would be withdrawn on a constant annual basis during this period of time. Only effective recharge would be available for development if the previously mentioned water-level constraints are to apply after 2030. The following table gives an estimate of the average annual ground-water availability of the Carrizo-Wilcox aquifer in terms of effective recharge and storage depletion in acre-feet to the year 2030.

	River Basin				
	Rio Grande	Guadalupe	San Antonio	Nueces	Totals
Wilcox Group annual effective recharge	4,400	23,200	19,800	21,400	68,800
Carrizo Formation annual effective recharge	9,300	15,400	23,600	57,300	105,600
Carrizo Formation annual storage depletion	2,700	7,900	17,300	159,600	187,500
Basin totals	16,400	46,500	60,700	238,300	361,900

Colorado, Brazos, and Trinity River Basins

Approximately 257,500 acre-feet (318 hm^3) of ground water as effective recharge is available annually for development in the Colorado, Brazos, and Trinity River basins from the Carrizo-Wilcox aquifer. This estimate is based on pumpage under assumed conditions (trough method) and is related primarily to the ability of the aquifer to transmit water from the outcrop area to the areas of pumping. Additional effective recharge above that calculated by the trough method is also assigned to the Wilcox Group based on the outcrop area of the Simsboro Sand Member. It is estimated that 10 percent of the average annual precipitation on the outcrop of the Simsboro could be effectively recharged and thus would be available on a perennial basis.

Although recharge from precipitation to the Carrizo-Wilcox aquifer appears to be more than adequate to supply the quantity of water that is calculated as effective recharge, the aquifer's transmission capacity limits the amount of annual effective recharge to a little less than 5 percent of the average annual rainfall falling on the Carrizo-Wilcox outcrop in these three river basins.

It is estimated that on the order of 443,500 acre-feet (547 hm^3) of ground water under artesian pressure in these three river basins can be withdrawn from storage. The procedure used to determine the recoverable storage first considered the transmissibility of the aquifer and the economic feasibility of pumping lift. Water recoverable from storage was equal to that amount released from artesian storage by the theoretical lowering of the hydraulic head (water level) to a maximum of 400 feet (122 m) below the land surface by innumerable discharge points lying in the area between the aquifer outcrop and the downdip limit of the bad water line (Figure 5). Water levels were lowered less than 400 feet below the land surface in two area strips, one adjacent to the outcrop where the depth to the top of the aquifer is less than 400 feet (122 m) and the other adjacent to and a distance of 5 miles (8 km) updip from the bad water line. The following steps were taken: (1) a map showing that part of the artesian pressure thickness within 400 feet of the land surface (See diagrammatic section in Figure 5) was constructed and contoured using a 100-foot interval; (2) the total volume for each 100-foot increment of artesian pressure thickness was determined; and (3) the sum of these volumes was multiplied by a coefficient of storage of 5.0×10^{-4} to obtain the total volume of water recoverable from artesian storage. This recoverable volume of water was then divided by 53 years (January 1, 1977, through December 31, 2029) to compute the annual storage depletion rate for 1977 to 2030. Although this water from artesian storage is available to support short-term pumpage in excess of the annual effective recharge, it should not be considered as water available for development on a sustained basis.

The following table gives an estimate of the average annual ground-water availability of the Carrizo-Wilcox aquifer in terms of effective recharge and storage depletion in acre-feet to the year 2030.

	River basin			
	Colorado	Brazos	Trinity	Totals
Carrizo-Wilcox aquifer annual effective recharge (trough method)	45,000	100,000	70,000	215,000
Simsboro Sand annual effective recharge	4,200	29,300	9,000	42,500
Annual storage depletion	900	3,500	4,000	8,400
Basin totals	50,100	132,800	83,000	265,900

Sulphur, Cypress, Sabine, and Neches River Basins

Approximately 213,000 acre-feet (263 hm^3) of ground water per year as annual effective recharge is available for development from the Carrizo-Wilcox aquifer in the Sulphur, Cypress, Sabine, and Neches River basins. This estimate is related to the capacity of the aquifer to transmit water from the outcrops to a line of theoretical discharge (trough method). The estimated annual effective recharge amounts to less than 5 percent of the average annual rainfall as applied to the Carrizo-Wilcox outcrop in these four river basins.

In addition to the annual effective recharge, about 358,600 acre-feet (442 hm^3) of ground water in these river basins can be withdrawn from artesian storage as described in the previous section. The storage estimated in this manner is economically recoverable and is divided by 53 years (January 1, 1977, through December 31, 2029) to give the annual storage depletion rate for 1977 to 2030. Although this source of water is available to support short-term pumpage in excess of the annual effective recharge, it should not be considered as water available for development on a sustained basis.

The following table gives an estimate of the average annual ground-water availability of the Carrizo-Wilcox aquifer in terms of effective recharge and storage depletion in acre-feet to the year 2030.

	River basin				
	Sulphur	Cypress	Sabine	Neches	Totals
Annual effective recharge	4,000	15,000	44,000	150,000	213,000
Annual storage depletion	100	800	1,400	4,500	6,800
Basin totals	4,100	15,800	45,400	154,500	219,800

The total average annual ground-water availability for the entire Carrizo-Wilcox aquifer in all river basins for the period from 1980 through 2029 is 847,600 acre-feet (1,050 hm^3) as shown in Table 1 and Appendix A. Included with this annual availability is a total annual effective recharge of 644,900 acre-feet (795 hm^3) which is 68,400 acre-feet (84.3 hm^3) or 12 percent more than the 1968 estimate of 576,500 acre-feet (711 hm^3). This increase was due to the inclusion of additional areas of the aquifer in northeast Texas and a re-evaluation of the annual effective recharge in all areas. Additionally, a certain amount of storage was considered to be depletable in the current analysis and was not included in the 1968 estimate.

Edwards (Balcones Fault Zone)

The Edwards (Balcones Fault Zone) aquifer consists of the Edwards and associated limestones of Cretaceous age which are in hydraulic continuity and consist of massive to thin-bedded, nodular, cherty, gypseous, argillaceous white to gray limestone and dolomite of the Georgetown, Edwards and Comanche Peak Formations. Thickness ranges from 200 to 600 feet (61 to 183 m). The Edwards Limestone is the primary water-bearing formation. It yields moderate to large quantities of fresh water and is characterized by its extensive honeycombed, cavernous strata caused by solution channeling over wide areas. Wells pumping from this aquifer are among the world's largest with some wells yielding more than 16,000 gal/min or 1,000 l/s (Peckham and others, 1968).

Hydrologic boundaries of the aquifer are formed by the overlying Del Rio Clay and the underlying Glen Rose Formation (Klemt and others, 1979). The lateral boundaries of the aquifer as shown in Figure 6 are (1) the edge of the Balcones Fault Zone on the north and northwest, (2) a ground-water divide near Brackettville which separates eastward underflow to the Nueces River basin from underflow to the Rio Grande basin on the west, (3) an extreme thinning of the aquifer near the Leon River between Salado and Temple in Bell County, and (4) a line which represents the downdip extent of water having less than 1,000 mg/l of dissolved solids. This line or boundary generally runs eastward through southern portions of Kinney, Uvalde, and Medina Counties and then northeastward through Bexar, Comal, and Hays Counties. The boundary in Travis, Williamson, and Bell Counties is represented by a line delineating the downdip extent of water having less than 3,000 mg/l of dissolved solids.

The Edwards is recharged primarily by downward percolation of surface water from streams traversing the outcrop and by direct infiltration of precipitation on the outcrop. This recharge reaches the aquifer mainly through crevices and faults in the Balcones Fault Zone. Because of the high rate of surface-water seepage into the underlying Edwards, some streams crossing the outcrop flow only during floods. In addition, small amounts of ground water enter the aquifer as lateral underflow from the Glen Rose Formation.

Water entering the Edwards aquifer generally moves toward natural discharge points which may or may not be in the river basin where the natural recharge occurs. These natural discharge points include Leona Springs near Uvalde, San Antonio and San Pedro Springs in San Antonio, Comal Springs in New Braunfels, San Marcos Springs in San Marcos, Barton Springs in Austin, Salado Springs in Salado, and numerous other smaller springs. Additionally, water is artifically discharged from the aquifer by hundreds of pumping wells. Much of the water that enters the aquifer as natural recharge in the Nueces River basin is actually withdrawn from the aquifer in the San Antonio River basin, and this portion is shown as effective recharge in the San Antonio River basin in Appendix A. Therefore, some of the aquifer's total effective recharge is shown in Appendix A in the river basin where the natural recharge occurred, and some in the river basin where it is developed.

Ground water withdrawn from the aquifer is generally fresh and is used for public supply, irrigation, industrial, domestic, and livestock watering purposes. Municipalities which rely on the aquifer for their water supply include San Antonio, Uvalde, Knippa, Sabinal, D'Hanis, Hondo, Castroville, La Coste, New Braunfels, San Marcos, Brackettville, Kyle, Georgetown, Round Rock, Jarrell, and numerous smaller communities.

Ground water moves rapidly through the Edwards aquifer. The volume of water in storage as well as the rate of spring flow may change rapidly in response to precipitation. For example, the depletion of water in storage caused by heavy pumpage during the drought years, 1948 through 1956, was almost completely restored during the wet years, 1957 and 1958.

Guadalupe, San Antonio, and Nueces River Basins

In 1971, as part of the regional study of the Guadalupe, San Antonio, and upper Nueces River basins, a comprehensive investigation of the Edwards (Balcones Fault Zone) aquifer was initiated. One of the principal objectives of the study was to obtain reliable hydrologic data and to develop and calibrate analytical techniques for use in the formulation of a total water resources development and management program for the Guadalupe, San Antonio, and upper Nueces River basins.

The technique developed to evaluate the aquifer was a computerized mathematical representation, or digital computer model, of the Edwards aquifer (Klemt and others, 1979). The purpose of the model was to simulate the response of water levels in the aquifer to pumpage and recharge for any given time period. Information derived from the model simulation included the areal distribution of water levels in the aquifer and flows from the major spring systems at any given time.

Prior to application of the computer model as a planning tool, it was calibrated. This meant that the parameters used in the model were estimated initially and then adjusted in order to accurately reproduce the aquifer's historical behavior. Measured spring flow, pumpage, recharge, and water levels during the period 1947-71 were utilized to calibrate the model. For each year of this period, pumpage and recharge values were assigned to the model at points where pumpage or recharge was observed to have occurred and for which data were available. The areal distribution of pumpage and recharge was based on field work conducted by personnel of the Department and the U.S. Geological Survey.

The distribution of simulation errors (difference between simulated water levels and measured water levels) was used as one indicator of the reliability of the model. The mean error in simulating January 1972 water levels throughout the aquifer (after simulating the aquifer for the period 1947-71) was 0.68 foot (0.21 m).

A comparison of simulated and measured spring flows was also used as an indicator of the reliability of the model. At the end of the simulation period, the difference between the cumulative simulated spring flow and the cumulative measured spring flow was small (4.3 percent of the total spring flow). For the last year, simulated and measured flows of Comal Springs were 160,000 (197 hm^3) and 159,200 acre-feet (196 hm^3), respectively. The difference amounted to less than 0.5 percent. This digital computer model of the Edwards (Balcones Fault Zone) aquifer was therefore considered to be calibrated to a degree of accuracy sufficient to reproduce past events. Consequently, it is felt that the model can be used to accurately predict future responses of the aquifer to specified conditions of recharge and pumpage.

The model was used to determine an average annual ground-water availability of the aquifer, defined as the rate of pumpage from the aquifer which would allow San Marcos Springs to continue flowing at an acceptable minimum annual rate of 34,000 acre-feet (41.9 hm^3) during a recurrence of the 1925-70 recharge sequence and which theoretically would prevent conditions conducive to the encroachment of saline water into the aquifer. Pumpage rates used in these simulations are presented in later paragraphs. No attempt was made to maintain the flow of Comal Springs since it was not considered feasible. Comal Springs are so closely associated hydrologically with water levels in the aquifer in the San Antonio area that a recurrence of the historical drought would cause discontinuance of flow even under current rates of pumpage. The maximum pumpage rate was determined by limiting the pumpage for irrigation and for municipal and manufacturing uses in Bexar County. These uses account for most of the pumpage from the aquifer.

Model simulations were performed for several pumpage rate limits, and a maximum annual pumpage rate of 425,000 acre-feet (524 hm^3) was found to allow acceptable spring flow (Figure 7). The acceptable minimum annual flow of San Marcos Springs equaled 34,000 acre-feet (41.9 hm^3). This is slightly below its recorded minimum annual flow of 44,000 acre-feet (54.3 hm^3) which occurred in 1956. Based on current water use and projected future water needs of the area that now uses this water-supply source, the maximum annual pumpage is not a water-supply limiting factor until the late 1980's. After that time, this constraint of pumpage will apply each year. The difference between the actual total projected pumpage of 844,700 acre-feet (1,042 hm^3) in the year 2030 and maximum allowable pumpage used in the computer model simulation is approximately 419,700 acre-feet (518 hm^3), of which 288,000 acre-feet (355 hm^3) represents annual projected municipal and manufacturing water demands in Bexar County for the year 2030. San Marcos Springs would continue to flow, but Comal Springs would cease flowing for 7 years beginning in 1999. The water levels will generally show a decline during a drought period. Relatively constant water levels will be expected since ground-water withdrawals generally will not exceed effective recharge.

For the purposes of this report, the average annual ground-water availability from the Edwards (Balcones Fault Zone) aquifer is defined as the average of the pumpage rates used in the model application. Since some areas will increase pumpage and other areas will reduce pumpage, averaging is considered to be an appropriate method of estimating water-supply availability based on the results of the model pumpage simulations. Withdrawals at these simulated average rates will preserve flow at San Marcos Springs regardless of when the severe drought occurs. The availability of water from the aquifer, assuming total pumpage does not exceed 425,000 acre-feet (524 hm^3) annually, will be 101,700 acre-feet (125 hm^3) per year in the Nueces River basin, 285,100 acre-feet (352 hm^3) per year in the San Antonio River basin, and 38,200 acre-feet (47.1 hm^3) per year in the Guadalupe River basin.

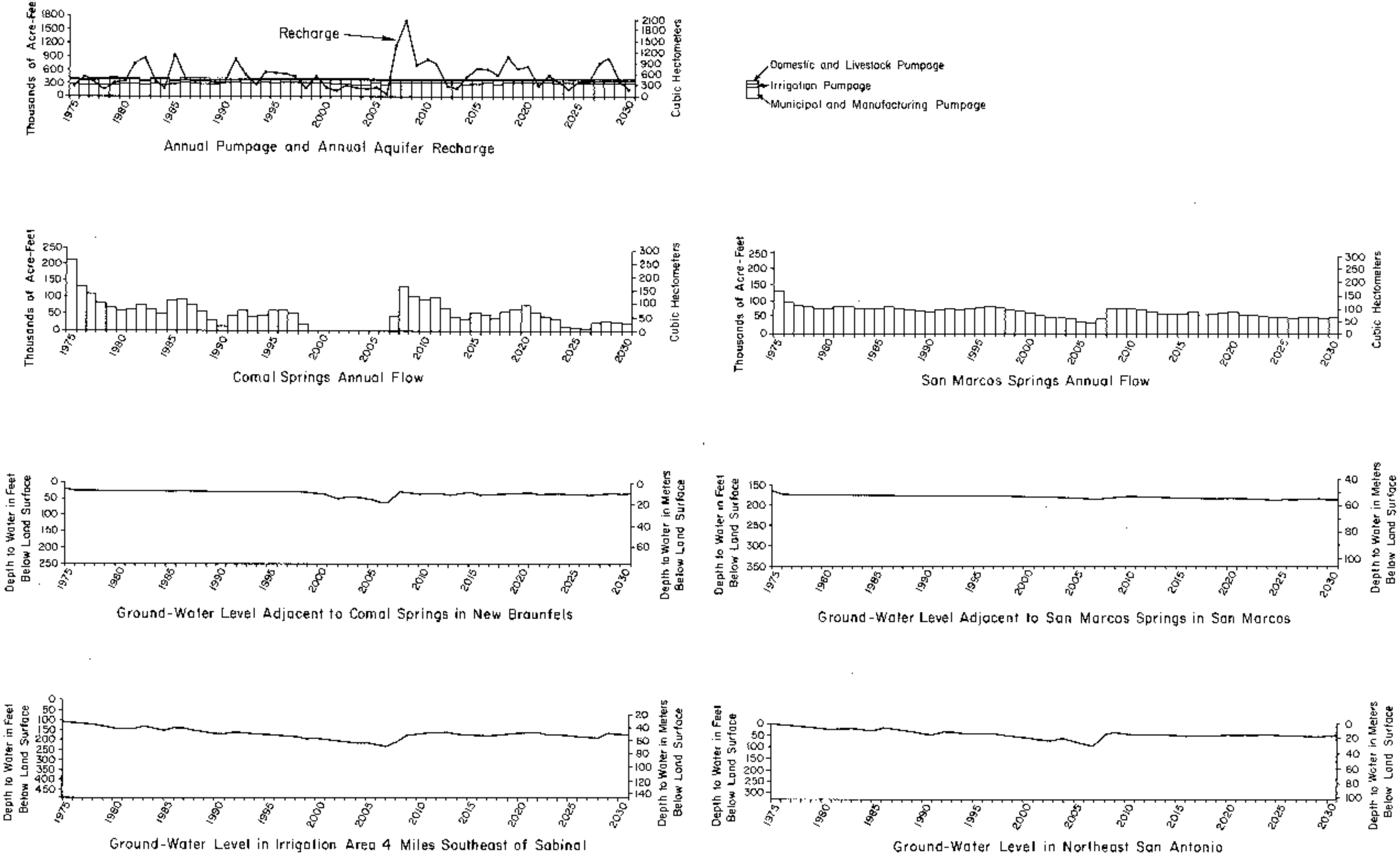
The principal conclusion which can be drawn from the above computer model application is that if total pumpage from the aquifer is limited to 425,000 acre-feet (524 hm^3) annually by jointly limiting pumpage for irrigation and municipal and manufacturing purposes in Bexar County, and if the assumed recharge sequence occurs, then San Marcos Springs will continue to flow during a recurrence of a severe drought period at a minimum annual discharge of 34,000 acre-feet (41.9 hm^3) and Comal Springs will eventually go dry. Extreme water-level declines would not occur and the potential for saline-water encroachment would be greatly reduced.

Colorado and Brazos River Basins

Approximately 8,700 acre-feet (10.7 hm^3) of ground water per year can be developed from the Edwards (Balcones Fault Zone) aquifer in the Colorado River basin (Appendix A). This estimate is based on the minimum spring flow at Barton Springs in Travis County which is water supplied by the effective recharge to the aquifer and not ground water in storage. Meinzer (1927) and U.S. Geological Survey surface-water records in 1956 reported minimum average annual flow at Barton Springs of approximately 8,688 acre-feet per year (10.7 hm^3) with the minimum all-time flow measured on March 29 of the same year (6,921 acre-feet or 8.5 hm^3 per year). These minimum flows were the result of the long drought of the 1950's which ended in 1957. Average flow for the period 1895-1972 was approximately 30,000 acre-feet (37.0 hm^3) per year. Withdrawals from the Edwards will directly affect streamflow and surface-water supply.

On the order of 5,000 acre-feet (6.17 hm^3) of ground water annually can be developed from the Edwards in the Brazos River basin (Appendix A). This availability estimate is based on minimum spring flow at Salado Springs in Bell County and the estimated Edwards ground-water withdrawals for 1956 in the Brazos River basin. Brune (1975) reported the minimum spring flow at Salado Springs was 3,330 acre-feet (4.11 hm^3) for 1956. Average flow for the period 1902-1972 was approximately 11,000 acre-feet per year (13.6 hm^3). Again, withdrawals from the Edwards will directly affect streamflow and surface-water supply.

The average annual ground-water availability for the entire Edwards (Balcones Fault Zone) aquifer in all river basins is 438,700 acre-feet, or 541 hm^3 (Table 1). This is an increase of 25,000 acre-feet (30.8 hm^3) or 6 percent over the 1968 estimate of 413,700 acre-feet (510 hm^3).



Annual Pumpage and Annual Aquifer Recharge

Comal Springs Annual Flow

San Marcos Springs Annual Flow

Ground-Water Level Adjacent to Comal Springs in New Braunfels

Ground-Water Level Adjacent to San Marcos Springs in San Marcos

Ground-Water Level in Irrigation Area 4 Miles Southeast of Sabinal

Ground-Water Level in Northeast San Antonio

Figure 7

Selected Results of Edwards Aquifer Model Application, Annual Pumpage Not Exceeding 425,000 Acre-Feet

Trinity Group

The Trinity Group aquifer is composed of the Paluxy, Glen Rose, and Travis Peak Formations. The Glen Rose Formation normally separates the Paluxy and Travis Peak Formations. However, along and west of a line which runs through Eastland, Comanche, and Brown Counties, the Glen Rose thins and is no longer a mappable unit. Here the Paluxy and the Travis Peak coalesce and become the Antlers Formation, although the term "Trinity Group" is retained. The Glen Rose Formation also pinches out on the north in Wise County near the City of Decatur; hence, the Antlers Formation is present north of this point. These basal Cretaceous-age rocks extend over a large area of north and central Texas (Figure 5) and are composed primarily of sand with interbedded clays, limestone, dolomite, gravel, and conglomerates. The thickness of the aquifer ranges from approximately 100 feet (30 m) in the outcrop areas to about 1,200 feet (366 m) in the downdip areas. Wells can yield as much as 2,000 gal/min (130 l/s), but in thinner sections of the aquifer most wells yield less than 100 gal/min or 6.3 l/s (Peckham and others, 1968).

Recharge to the aquifer is primarily in the form of infiltration of precipitation and seepage of surface water from lakes, unlined earthern ponds, streams, and return flows of water used to irrigate crops on the aquifer's surface.

In the outcrop area, the sands and gravels of the Antlers and Travis Peak Formations are not completely water saturated, thus water-table conditions prevail. The aquifer is artesian downdip as a result of being overlain by relatively impervious limestones and shales of younger formations (Klemt and others, 1975).

Water quality is acceptable for most municipal and industrial purposes; however, the fluoride content in many places exceeds the U.S. Environmental Protection Agency's Safe Drinking Water Act Interim Primary Standards for municipal supplies. Irrigation is extensive in Comanche, Eastland, and Erath Counties where dissolved solids generally do not exceed 500 mg/l. Toward the east, where the aquifer becomes deeply buried, usable quality water (less than 3,000 mg/l) occurs to depths of about 3,500 feet (1,070 m).

The aquifer has been overdeveloped in the Dallas-Fort Worth metropolitan area and in the vicinity of Waco. In 1977, water levels in the Dallas-Fort Worth area ranged from about 400 to about 1,200 feet (122 to 366 m) below land surface, and in the Waco area, they ranged from about 200 to greater than 400 feet (61 to 122 m) below the surface of the ground. As the use of ground water continues from the Trinity aquifer in these areas, water levels will continue to decline since withdrawals exceed effective recharge which is severely limited by the aquifer's relatively low transmissibility. Water-quality problems, such as encroachment at the fresh-salt water interface and pumping costs, will increase as water levels continue to be excessively lowered in the aquifer.

Because of the previously described hydrologic and geologic interrelationships of the Paluxy, Glen Rose, Travis Peak, and Antlers Formations, the amount of ground water available for future development was determined collectively for all of these units which together are called the Trinity Group aquifer. The amount of water available for development was based on the trough method in combination with a percentage of the average annual precipitation on the Trinity outcrop as effective recharge and estimates of depletable artesian storage. The annual effective recharge is 95,100 acre-feet or 117 hm^3 (Table 1 and Appendix A).

Within the Brazos, Trinity, and Red River basins, the annual effective recharge was determined, for the most part, using the trough method. Utilizing this method, the transmission capacity of the aquifer was calculated by assuming that water levels were lowered along a line approximately parallel to the outcrop trend and at the top of the aquifer where the depth was 400 feet below the land surface. Using these limitations and provided that sufficient water is available from precipitation, it was determined that approximately 1.5 percent of the average annual precipitation falling on the outcrop (effective recharge) can be transmitted through the Trinity Group aquifer to supply the assumed withdrawals on a sustained basis (Price, 1979).

Within and west of the main aquifer in the Brazos, Trinity, and Red River basins, as well as in the Colorado River basin, there are outliers of surficial deposits of sand, gravel, and limestone which also contain usable quality ground water. These aquifers are also considered a part of the Trinity Group aquifer. They are located in Callahan, Coleman, Taylor, Runnels, Nolan, Mitchell, and Coke Counties. The annual effective recharge for these areas was determined as follows. Previously, an effective recharge rate of 1.58 percent of the average annual precipitation was determined for the limestones of the Concho, San Saba, and north Llano River drainage basins. This recharge rate was applied to those areas where the Antlers was overlain by limestone. In areas where sandstone was present in the outcrop and was generally less permeable than the limestone, the percentage for effective recharge was reduced to 1.5 percent of the average annual precipitation.

It is estimated that on the order of 1 million acre-feet (1,250 hm^3) of ground water in the Brazos, Colorado, Red, Sabine, Sulfur, and Trinity River basins can be withdrawn from artesian storage (Table 1 and Appendix A). The depletable artesian storage was determined by using a geological structure map of the top of the Trinity Group aquifer and water-level observation well measurements and then computing the difference between the water-level elevation and the elevation 100 feet (30 m) above the top of the aquifer (Figure 7). The top of the Antlers Formation was designated as the top of the Trinity Group in southern Cooke, Grayson, Fannin, northern Denton, and Collin Counties. South of these counties, the top of the Paluxy Formation was designated as the top of the Trinity Group aquifer except in McLennan, Bell, Milam, Williamson, and Travis Counties where the top of the Travis Peak Formation was specified as the top of the aquifer. A contour interval of 500 feet (152 m) was used. The area in which artesian storage was contoured excluded areas within 5 miles (8 km) of the downdip limit of fresh to slightly saline water, within 5 miles of the Texas-Oklahoma Border, and within 5 miles of the Colorado River, and included only the area where 100 feet (30 m) or more of artesian head was present above the top of the Trinity Group aquifer. This area was determined by using a planimeter and then was multiplied by the contoured artesian storage thickness and the artesian storage coefficient, 1×10^{-4}, to yield the volume of water recoverable from artesian storage.

The average annual ground-water availability for the Trinity Group aquifer was determined by dividing the volume of water recoverable from storage by 53 years—the planning period 1977 to 2030—and adding it to the estimated annual effective recharge.

The total average annual ground-water availability for the entire Trinity Group aquifer in all river basins for the period from 1980 through 2029 is 114,100 acre-feet or 131 hm^3 (Table 1 and Appendix A). Included with this average annual availability is a total annual effective recharge of 95,100 acre-feet (117 hm^3), which is an increase of 24,900 acre-feet (30.7 hm^3) or 35 percent over the 1968 estimate of 70,200 acre-feet (86.6 hm^3). This increase was due to a re-evaluation of the effective recharge of the aquifer as well as the inclusion of additional areas of the aquifer in north-central Texas. Additionally, water in artesian storage was not included in the 1968 estimate.

Alluvium and Bolson Deposits

Tertiary to Holocene age water-bearing alluvium and bolson deposits are scattered throughout many areas of the State. Even though these sediments are completely separated geographically, they are geologically and hydrologically similar and, collectively, are considered as a single major aquifer. The origin of the alluvial sediments can be from deposition by streams (alluvium deposits), by wind (eolian deposits), and in playa-type lakes (lacustrine deposits). They are generally composed of unconsolidated, alternating and discontinuous beds of silt, clay, sand, gravel, and boulders. Caliche, gypsum, conglomerate, volcanic ash, tuffs, and basalt are also associated with these sediments. Bolson deposits usually originate as outwash from adjacent highlands and are deposited as intermontane or valley sediments. The areal extent of these aquifers is delineated on Figure 6.

In some areas, these deposits contain comparatively large volumes of ground water. The five largest and most productive areas of these aquifers are the alluvium and bolson deposits in the westernmost Texas region, the Cenozoic Alluvium of West Texas, the alluviums of North-Central Texas, the Leona Alluvium of Tom Green County, and the Brazos River Alluvium of Southeast Texas. Ground water also exists in other river alluviums of the State, especially in eastern Texas; however, these are relatively minor occurrences and the data are too scarce to fully evaluate these scattered alluvium deposits.

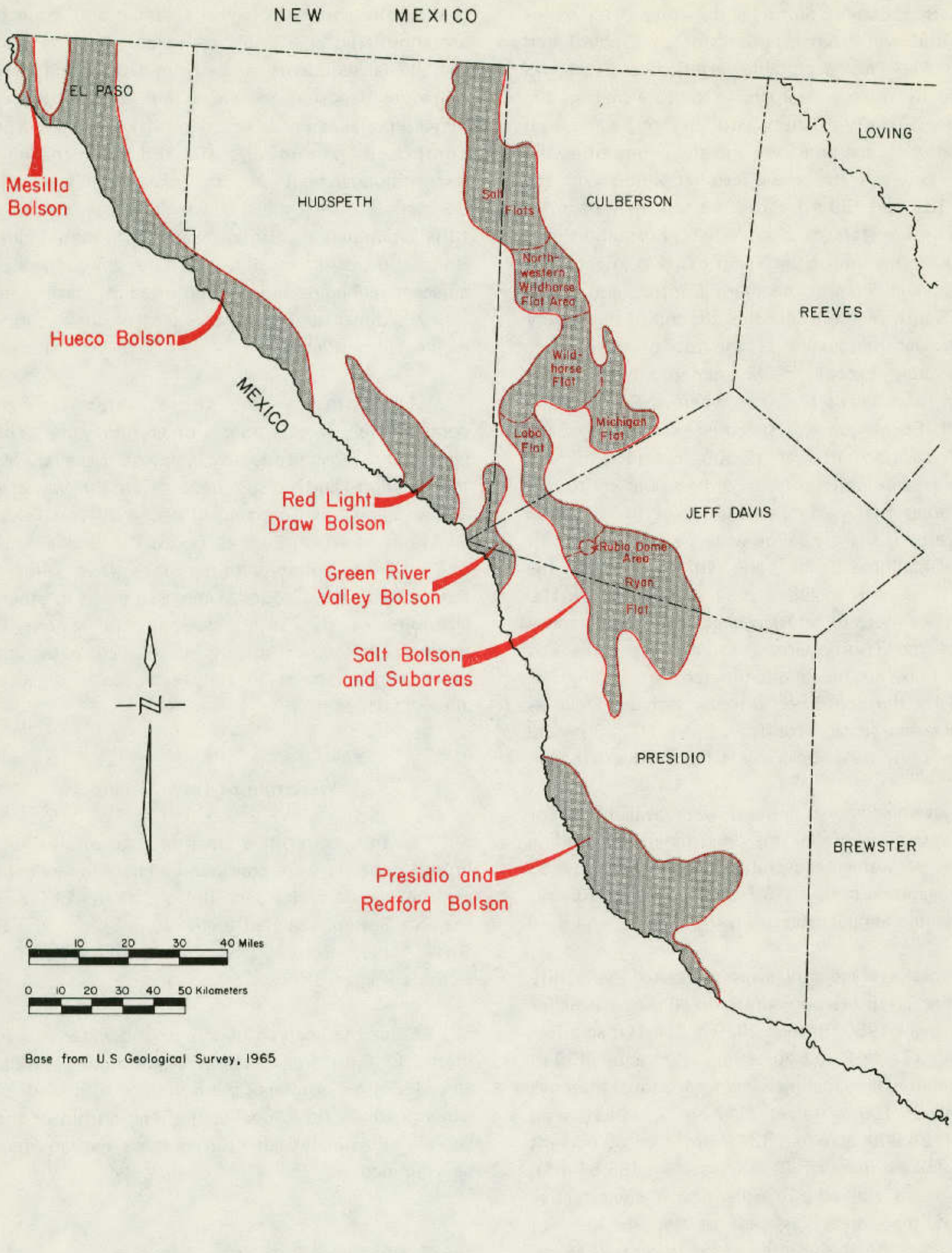
Westernmost Texas Region

In this region, five separate areas of alluvium and bolson deposits were considered. These individual areas are the Mesilla and Hueco Bolsons of the El Paso area, the Salt Bolson, the Red Light Draw Bolson, the Green River Valley Bolson, and the Presidio and Redford Bolsons (Figure 8).

Since the analysis of the ground-water availability in the El Paso area depends on both the Mesilla and Hueco Bolson aquifers, these will be discussed jointly when possible. Additionally, the relationship of the Rio Grande alluvium which overlies these two aquifers will be examined.

Mesilla and Hueco Bolsons

The Mesilla Bolson aquifer is located in the extreme western corner of Texas in El Paso County. It lies west of the Franklin Mountains and extends along the Rio Grande Valley northward into New Mexico and southwestward into Mexico. Deposits of the Hueco Bolson aquifer lie principally in a north-trending, trough-like depression between the Franklin and Hueco



Base from U.S. Geological Survey, 1965

Figure 8

Alluvium and Bolson Aquifers of the Westernmost Texas Region

Mountains in north-central El Paso County. The bolson also extends into New Mexico to the north; into the State of Chihuahua, Mexico to the south; and into Hudspeth County to the southeast. Very little usable quality ground water is present in the Hueco Bolson in Hudspeth County and these deposits, therefore, are not considered further (Gates and Stanley, 1976). Bolson deposits of both the Mesilla and Hueco aquifers are the major source of ground water for municipal and industrial needs of the City of El Paso.

The Rio Grande alluvium overlies the bolson deposits in the Mesilla and El Paso Valleys (the Rio Grande Valley above and below the City of El Paso, respectively). The Rio Grande alluvium, which reaches a maximum thickness of about 200 feet (61 m), is an important source of shallow ground water for supplemental irrigation when the surface-water flow in the Rio Grande is not sufficient to meet the total agricultural water needs of the valley farmers.

The bolson deposits have a total thickness of approximately 2,000 feet (610 m) near the City of El Paso in the Mesilla Bolson (Leggat and others, 1962, p. 14) and about 9,000 feet (2,743 m) in the Hueco Bolson area (Bluntzer, 1975, p. 3). In places, these deposits contain fresh ground water to depths of about 1,200 feet or 366 meters (Bluntzer, 1975). The quality of ground water varies both areally and with depth in the Mesilla Bolson and may range from fresh to moderately saline (Alvarez and Buckner, 1979).

Well yields vary from small to as large as 3,000 gal/min (190 l/s). Large-capacity wells completed in the Mesilla and Hueco Bolsons usually yield from 1,000 to 2,000 gal/min (63 to 130 l/s). Most of the wells in the Rio Grande alluvium are used for irrigation purposes and well yields range from 25 to 3,015 gal/min (1.6 to 190 l/s) with most wells yielding greater than 1,000 gal/min (63 l/s).

The Texas Department of Water Resources, the U.S. Geological Survey, and the City of El Paso have conducted investigations to determine the ground-water availability from the Mesilla and Hueco Bolsons. Since these aquifers are the key source of water in the El Paso area, it is imperative to analyze their future capabilities to meet projected requirements. However, before this can be done, it is necessary to consider three other sources of water supply that also aid in meeting the projected requirements; namely, annual surface-water deliveries from the Rio Grande to the City of El Paso, annual effective recharge to the bolsons, and induced recharge to the bolsons from the Rio Grande and from storage in the Rio Grande alluvium.

The total projected water requirements as shown in Table 2 are based in part on the historical water use for the El Paso area and were estimated using Department projections developed in 1977 (Texas Water Development Board, 1977). The total projected requirements include water for domestic, municipal, manufacturing, power, mining, and livestock purposes. These total projected requirements do not include water to be used for irrigation from the Rio Grande alluvium in El Paso County.

Table 2.—Estimated Total Water Use and Projected Water Requirements, El Paso Area

Selected year	Total use and projected requirement (acre-feet)	Surface water from the Rio Grande (acre-feet)	Ground-water from Mesilla and Hueco Bolsons (acre-feet)
1974	111,900	14,200	97,700
1980	137,000	13,500	123,500
1990	180,000	13,900	166,100
2000	225,600	16,900	208,700
2010	294,100	17,900	276,200
2020	362,500	18,700	343,800
2030	431,400	20,100	411,300

Through consultation with staff members of the City of El Paso Water Utilities, projected surface-water deliveries from the Rio Grande to the city were developed (Table 2). These projected annual surface-water deliveries were subtracted from the total projected requirements to obtain the total ground-water requirements that must be met by effective recharge, induced recharge, and depletion of water recoverable from storage, as expressed by the following equation:

$$R_{GW} = ER + IR + SD,$$

where R_{GW} is the total requirement to be met from ground water, ER is the effective recharge to the bolsons, IR is the induced recharge, and SD is the depletion of water recoverable from storage.

Leggat and others (1962, p. 18) calculated the annual effective recharge to the Mesilla Bolson aquifer to be 18,000 acre-feet (22.2 hm^3). Computer model studies of the Hueco Bolson aquifer determined the effective recharge at about 6,000 acre-feet (7.40 hm^3) per year (Meyer, 1976).

When the Mesilla and Hueco Bolsons are pumped heavily, significant quantities of ground water enter these aquifers as induced recharge—expressed as a percentage of the ground water pumped—from the Rio Grande and from storage in the Rio Grande alluvium. This induced recharge was substantiated when computer model studies were conducted by the U.S. Geological Survey and compared with observations and measurements of water levels in the Hueco Bolson aquifer (Meyer, 1976). After making necessary adjustments, the induced recharge was assumed to apply to the Mesilla Bolson aquifer. The induced recharge was considered a function of the pumpage, which in turn depends on the future availability of ground water. Table 3 shows the schedule for the induced recharge as a percentage of the ground-water pumpage used for the Mesilla and Hueco Bolson aquifers in this analysis.

Table 3.—Schedule for Induced Recharge As a Percentage of Ground-Water Pumpage in the Mesilla Bolson and Hueco Bolson Aquifers

MESILLA BOLSON AQUIFER

Year or time period	Percent of ground-water pumpage
1974	25
1975	29
1976	33
1977-2010	36
2011-2020	33
2021-2030	30

HUECO BOLSON AQUIFER

Time period	Percent of ground-water pumpage
1974-2000	36
2001-2005	33
2006-2010	30
2011-2015	27
2016-2020	24
2021-2025	21
2026-2030	18

The percentages of ground-water pumpage presented in the above data and used to determine induced recharge have been adjusted based on the assumption that the river and alluvium storage will be capable of supplying large quantities of water. Unforeseen limiting factors, however, are the availability of water from the river, lining of the river and canals, and other possible uses of ground-water storage in the Rio Grande alluvium.

At the end of 1973, it was estimated that the Mesilla Bolson aquifer contained about 560,000 acre-feet (690 hm^3) of fresh ground water in storage in Texas and the Hueco Bolson aquifer had approximately 10.6 million acre-feet or 13,100 hm^3 (Leggat and others, 1962, p. 38; Meyer and Gordon, 1972; and Meyer, 1976). Even though all of this fresh water in storage is considered recoverable, the proximity of poor quality ground water to it requires the constraint that only 75 percent of the fresh water in storage will be pumped to meet the requirements through 2030 in the El Paso area. In 2031, there would be approximately 140,000 acre-feet (173 hm^3) and 2.73 million acre-feet (3,370 hm^3) remaining in storage in the Mesilla and Hueco Bolsons, respectively; or a total of 2.87 million acre-feet (3,540 hm^3) which is about 25 percent of the total amount of fresh water in storage in El Paso County in 1974.

In 1984, the Mesilla Bolson aquifer will reach its maximum capability to meet its portion of the ground-water requirements ($R_{GW} = ER + IR + SD$ for the El Paso area) in that a continued increase in the rate of depletion of storage, SD, would result in less than 25 percent remaining in storage after 2030. Therefore, that portion of the ground-water requirements shown in Table 2, which cannot be met by the Mesilla Bolson aquifer as an increase in the rate of depletable storage, was transferred as an increased requirement of the Hueco Bolson aquifer (Table 4). At the beginning of the analysis, the total projected ground-water requirements were divided between the Mesilla and Hueco Bolsons based on 1974 data and the capabilities of the aquifers in 1974. However, in about 1984 the Mesilla Bolson aquifer's capability to provide storage became limited and the amount of annual storage depletion, SD, was held constant at approximately 8,500 acre-feet (10.5 hm^3) per year from 1984 through 2030. During this period of the analysis, the effective recharge, ER, was kept constant at 18,000 acre-feet (22.2 hm^3) per year as it was from 1974 to 1984, but the induced recharge varied as shown in Tables 3 and 5. Therefore, the quantity of ground water supplied from the Mesilla Bolson aquifer will decrease after the year 2010, as indicated in Tables 4 and 5, because of the decrease in induced recharge, IR.

Table 4.—Ground-Water Adjustment of the Requirement of Depletable Storage From the Mesilla Bolson to the Hueco Bolson in Acre-Feet

Selected year	Ground-water requirement from the Mesilla and Hueco Bolsons from Table 2	Average annual ground-water availability from Appendix A		
		Adjustment	Mesilla Bolson	Hueco Bolson
1974	97,700	0	24,100	73,600
1980	123,500	0	32,900	90,600
1990	166,100	5,600	41,400	124,700
2000	208,700	19,700	41,400	167,300
2010	276,200	33,000	41,400	234,800
2020	343,800	48,100	39,500	304,300
2030	411,300	63,100	37,800	373,500

Ground-water availabilities for the Mesilla Bolson and Hueco Bolson aquifers which resulted from this analysis are given in Tables 4, 5, and 6 and in Appendix A.

Under the conditions of this analysis of the Mesilla Bolson and Hueco Bolson aquifers, it is possible that the ground water remaining in storage in 2031 and some of the ground water withdrawn between 1974 through 2030 will be slightly saline because of saline-water encroachment from the induced recharge source and movement of slightly to moderately saline ground water from adjoining bolson deposits. Even though the future salinity of the water is not predictable, proper management of withdrawals from the aquifers such as "in well" blending of the fresh and slightly saline ground water from each bolson will possibly be necessary. The quantities of ground water shown to be available by the use of these two analyses probably can be withdrawn in absence of extreme water-quality problems.

The analysis and its results did not consider ground-water development of these bolsons in Mexico and New Mexico. Development in these two areas adjacent to Texas could adversely affect the availability estimates presented here. In this respect, the most critical area lies in the artesian zone of the Hueco Bolson aquifer in Mexico where Ciudad Juarez is pumping large amounts of ground water just across the Rio Grande from the City of El Paso.

If unacceptable ground water quality degradation should occur, then the City of El Paso and other large ground-water users in El Paso County must import fresh water, solve local desalting water resource problems, and pump less ground water and reclaim existing return flows. Sources of import water for El Paso County within Texas are few. The closest possible Texas sources of fresh water in limited quantities are in the Red Light Draw Bolson about 100 miles (161 km) southeast of the City of El Paso and the southern portion of the Salt Bolson approximately 150 miles (241 km) southeast of the city. The nearest sources of fresh ground water for import are in New Mexico adjacent to El Paso County. In 1974, the northern extension of the Hueco Bolson into New Mexico may have had as much as 6.2 million acre-feet (7,650 hm^3) of fresh water in storage and as much as 2.9 million acre-feet (3,580 hm^3) of slightly saline water in storage (Meyer, 1976; and Bluntzer, 1977). The other areas in New Mexico which have large but undetermined amounts of fresh ground water are the Mesilla Valley and the large Mesilla Bolson proper west of the Mesilla Valley. However, New Mexico law

Table 5.—Average Annual Ground-Water Availability for Selected Years for the Mesilla Bolson Aquifer of El Paso County, Texas

	Year						
	1974	1980	1990	2000	2010	2020	2030
Ground-water requirement (pumpage), acre-feet[1]	24,100	32,900	41,400	41,400	41,400	39,500	37,800
Average annual effective recharge, acre-feet	18,000	18,000	18,000	18,000	18,000	18,000	18,000
Induced recharge, acre-feet (%)	6,100 (25.2%)	11,800 (36%)	14,900 (36%)	14,900 (36%)	14,900 (36%)	13,000 (33%)	11,300 (30%)
Storage depletion, acre-feet	0	3,100	8,500	8,500	8,500	8,500	8,500
Amount remaining in storage at end of year, acre-feet	560,000	553,400	479,500	394,600	309,700	224,800	140,000[2]

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[1] See Table 2 for analysis of ground-water requirement.

[2] Approximately 75 percent of the initial total storage has been "mined" with 25 percent remaining.

Table 6.—Average Annual Ground-Water Availability for Selected Years for the Hueco Bolson Aquifer of El Paso County, Texas

	Year						
	1974	1980	1990	2000	2010	2020	2030
Ground-water requirement (pumpage), acre-feet[1]	73,600	90,600	124,700	167,300	234,800	304,300	373,500
Average annual effective recharge, acre-feet	6,000	6,000	6,000	6,000	6,000	6,000	6,000
Induced recharge, acre-feet (%)	26,500 (36%)	32,600 (36%)	44,900 (36%)	60,200 (36%)	70,500 (30%)	73,000 (24%)	67,200 (18%)
Storage depletion, acre-feet	41,100	52,000	73,800	101,100	158,400	225,300	300,300
Amount remaining in storage at end of year, acre-feet[2]	10,600,000	10,274,200	9,647,700	8,759,800	7,416,900	5,434,100	2,730,000[3]

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[1] See Table 2 for analysis of ground-water requirement.

[2] Approximately 10.6 million acre-feet of ground water was in total storage as of January 1, 1974.

[3] Approximately 74 percent of the initial total storage has been "mined" with 26 percent remaining.

presently precludes the export of ground water outside of New Mexico borders.

Proper management of the valuable ground-water resource in the El Paso area must of necessity entail the utilization of computer modeling techniques to keep abreast of the changing conditions.

Salt Bolson

The Salt Bolson extends along a winding course from its uppermost reaches in northeastern Hudspeth County southward across western Culberson and Jeff Davis Counties into north-central Presidio County (Figure 8). It is further divided into its principal subareas of Salt Flats, Wildhorse Flat and its northwestern extension, Michigan Flat, Lobo Flat, Ryan Flat, and the Rubio Dome area. Even though the deposits in these subareas generally have the characteristics of alluvial sediments, lithologic differences may exist among them depending on the origin of the fill material, such as, volcanic, lacustrine, and alluvial.

The sediments in Salt Flats are composed of lacustrine clay and sand that are saturated with mostly saline ground water with insignificant amounts of fresh to slightly saline water. Consequently, this is the only subarea in the Salt Bolson where irrigation is not possible.

In Wildhorse Flat, the fill material is composed mostly of coarse- to fine-grained alluvial fan deposits. These bolson deposits are as much as 2,400 feet (732 m) thick but over large areas range in thickness from 1,000 to 1,200 feet (305 to 366 m). A test hole drilled at the Culberson County Airport near Van Horn penetrated 1,250 feet (381 m) of fill which was well cemented and of low permeability below the 1,000-foot (305-m) depth. Large-capacity irrigation wells that have been drilled in the northern part of Wildhorse Flat yield from 400 to 1,200 gal/min (25 to 76 l/s). Water levels are declining about 1 foot (0.3 m) per year. The ground-water quality in the northwestern Wildhorse Flat area ranges from fresh to slightly saline along the western edge, slightly saline to moderately saline along the east side, and very saline in most of this area proper (Figure 8). Around Van Horn, in the southern Wildhorse Flat area, the water quality varies from 350 to 500 mg/l dissolved solids. Elsewhere in Wildhorse Flat, the dissolved solids range from 1,000 to 2,000 mg/l.

The Michigan Flat area contains lacustrine-type deposits of mostly fine-grained sand with clay that range in thickness from 400 feet (122 m) to over 600 feet (183 m). Large-capacity wells may yield over 2,000 gal/min (130 l/s). Water levels are declining about 1 to 3 feet (0.3 to 0.9 m) per year. The quality of the ground water ranges from 1,000 to 2,000 mg/l dissolved solids.

Sediments in the Lobo Flat area are indicative of deposits having a volcanic source as well as lacustrine and alluvial sedimentary history. The fill material is composed primarily of volcanic clastic deposits underlain by igneous rocks which are probably in hydrologic continuity. These underlying igneous rocks consist of lava flows and compacted ash tuffs which characteristically have low permeability except where there is fracturing. The thickness ranges from 1,400 to 1,900 feet (427 to 579 m). Well yields vary from 400 to 1,400 gal/min (25 to 88 l/s) depending on the permeability of the formation penetrated. Water levels are declining at the rate of 1 to 6.5 feet (0.3 to 2.0 m) per year as determined during a 22-year period from 1951 to 1973. The upper part of the fill and volcanics of Lobo Flat contains fresh water that ranges from 300 to 400 mg/l dissolved solids.

The Ryan Flat and Rubio Dome areas lie in the most southern extension of the Salt Bolson and are composed of sediments that indicate volcanic, lacustrine, and alluvial depositional histories. Deposits in Ryan Flat range from 740 feet (226 m) thick near the Davis Mountains to 4,300 feet (1,311 m) thick near Valentine in Jeff Davis County. A test hole in Ryan Flat penetrated 1,250 feet (381 m) of permeable material. Little ground-water development has occurred in the Ryan Flat and Rubio Dome areas and detailed hydrologic information is scarce; however, it is reported that well yields range from 250 to 1,400 gal/min (16 to 88 l/s).

Evaluation of the Salt Bolson relied heavily on data collected by geophysical methods, namely by earth resistivity sounding techniques and supportive test hole drilling. Also, airborne electromagnetic procedures and selected data provided by several oil companies, such as seismic refraction and reflection information, aeromagnetic studies, and gravity surveys (Gates and others, 1978) were used in the analysis of this aquifer.

An estimate of the annual effective recharge was determined by assuming 1 percent of the mean annual precipitation (Gates and others, 1978) over the outcrop area. The annual effective recharge to all of the subareas of the Salt Bolson was calculated to be 14,000 acre-feet or 17.3 hm^3 (Table 7).

The amount of ground water in storage in the Salt Bolson was determined primarily by utilizing the information obtained from the geophysical studies, comparisons of pumpage and water-level declines, and

Table 7.—Summary of Annual Effective Recharge and Ground-Water Storage in the Salt Bolson and Subareas, 1976

Subarea	Annual effective recharge (acre-feet)	Fresh water in storage (million acre-feet)	Slightly saline water in storage (million acre-feet)	Recoverable storage[1] (million acre-feet)
Wildhorse Flat	6,000	1.52	1.03	1.9125
Michigan Flat	[2]	.42	Insufficient data	.3150
Lobo Flat (northern and central Lobo Flat)	2,000	.54	insignificant	.4050
Southern Lobo Flat and adjacent area (Chispa Flat)	[3]	.73	do	.5475
Rubio Dome area	[4]	.43	do	.3225
Ryan Flat	6,000	2.90	do	2.175
TOTALS	14,000	6.54	1.03	5.6775

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[1] 75 percent of the fresh- to slightly-saline water in storage.
[2] Included in amount for Wildhorse Flat.
[3] Included in amount for Lobo Flat.
[4] Part of annual effective recharge included with Southern Lobo Flat and adjacent area and the balance is included with the Ryan flat area.

other supportive geohydrological data. In Wildhorse and Michigan Flats, these methods were used to find the saturated thicknesses and specific yield. The specific yield was found to be 13 percent but was subsequently reduced to 10 percent because of less porosity in the lower sediments. In Lobo Flat, Rubio Dome, and Chispa Flat (in southern portion of Lobo Flat) areas, 5 percent was used as the average specific yield. The saturated thickness was estimated to be from 520 to 575 feet (158 to 175 m) in the Lobo and Chispa Flats and about 350 to 400 feet (107 to 122 m) in the area around Rubio Dome. Data were not available to determine the specific yield in Ryan Flat and vicinity; therefore, a conservative estimate of 7.5 percent was used. Based on the geophysical evidence obtained in the area, an average of 1,000 feet (300 m) was used for the saturated thickness.

Throughout the Salt Bolson, 75 percent of the fresh to slightly saline ground water was considered to be recoverable. As such, the average annual ground-water availability to the year 2030 was determined in the following manner: (a) the amount of ground water estimated to be recoverable from storage was divided by 54 years (January 1, 1976 through December 31, 2029) to find the annual storage depletion rate, and (b) this depletion rate was added to the annual effective recharge of the area being evaluated.

In addition to the annual effective recharge for the Salt Bolson and its subareas, Table 7 also shows the quantity of fresh ground water in storage as 6.54 million acre-feet (8,060 hm^3), the volume of slightly saline water as 1.03 million acre-feet (1,270 hm^3), and the total recoverable storage of fresh to slightly saline water as approximately 5.68 million acre-feet (7,000 hm^3). Additional reference to the Salt Bolson availability is made in Appendix A.

Red Light Draw Bolson

The Red Light Draw Bolson is located in the southeastern corner of Hudspeth County (Figure 8). It is bordered on the southwest by the Quitman Mountains, on the north by Devil Ridge and Eagle Mountain, and extends southeastward to the Rio Grande (Gates and others, 1978). The bolson fill consists of coarse-grained alluvial fan deposits as revealed by the Guerra No. 1 test hole which penetrated 1,100 feet or 335 m (Gates and others, 1978). Additionally, seismic refraction velocity surveys indicate that the bolson fill in the southeastern portion is underlain by volcanic rocks which are possibly well cemented. Here, the fill and volcanic rocks probably are as much as 3,600 feet (1,097 m) thick. In the northwestern portion of Red Light Draw, the fill is generally less than 500 feet (152 m) thick and mostly unsaturated.

Most wells in Red Light Draw are livestock wells of small yield; however, irrigation wells located near the Rio Grande in the floodplain alluvium reportedly yield between 1,000 and 1,500 gal/min (63 to 95 l/s).

The ground water in the bolson fill usually is fresh and has a dissolved-solids content of less than 500 mg/l. Near the Rio Grande, the water quality deteriorates and is commonly saline to very saline.

Using 1 percent of the mean annual rainfall, the annual effective recharge was estimated to be 2,000 acre-feet (2.47 hm^3) over the drainage area of the aquifer (Gates and others, 1978).

As of 1976, the total amount of ground water stored in the deposits of Red Light Draw was estimated to be approximately 600,000 acre-feet (740 hm^3). This estimate is based on a saturated thickness of 350 to 450 feet (107 to 137 m), an area of 32 square miles (83 km^2), and a specific yield of 7.5 percent. This specific yield was used because of the similarity of the materials of this aquifer with the materials of the Lobo and Ryan Flats subareas of the Salt Bolson from which the estimate was obtained. It is estimated that 450,000 acre-feet (555 hm^3) or 75 percent of the water in storage can be recovered.

Green River Valley Bolson

The Green River Valley Bolson is very similar to the Red Light Draw area. It lies in the four corner county area of Hudspeth, Culberson, Jeff Davis, and Presidio Counties and is bordered by the Eagle Mountains on the west, Van Horn Mountains on the east, and the Rio Grande on the south (Figure 8). In this erosional valley of bolson fill, the deposits are composed of coarse-grained sediments in many places, but considerable amounts of fine-grained material exist along the valley axis. These fine-grained deposits are thought to be lacustrine clay and silt. They contain "salty" water. The U.S. Geological Survey Davis No. 1 test hole penetrated 2,012 feet (613 m) of mostly brown clay with thin beds of sand and gravel without reaching consolidated rock (Gates and others, 1978). The average thickness of the bolson is about 750 feet (229 m), and it reaches a maximum thickness of 2,800 feet (853 m) near the Rio Grande where tuff may underlie the fill.

Only a few low yield livestock wells pump from this aquifer. A limited number of irrigation wells are located on the floodplain near the Rio Grande. Yields from these wells are reported to be between 1,000 and 1,500 gal/min (63 to 95 l/s).

The ground water in most of the basin fill is fresh and usually contains less than 500 mg/l dissolved solids. Near the Rio Grande, the water quality is commonly saline to very saline.

Again, the annual effective recharge was determined by using 1 percent of the mean annual precipitation over the outcrop of 12 square miles (31 km^2). Thus, the effective recharge was estimated to be 1,000 acre-feet or 1.23 hm^3 (Gates and others, 1978).

By using a range of saturated thicknesses of 450 to 550 feet (137 to 168 m) and a specific yield of 7.5 percent based on similarities of this aquifer to subareas of the Salt Bolson, which have specific yields of 7.5 percent, 280,000 acre-feet (345 hm^3) of fresh water was estimated to be in storage in 1976. Of this amount, approximately 210,000 acre-feet (259 hm^3) or 75 percent is assumed to be recoverable.

Presidio and Redford Bolsons

The Presidio and Redford Bolsons outcrop in an area of south-central Presidio County along and on the north side of the Rio Grande from south of the community of Candelaria to about 10 miles (26 km) southeast of Presidio (Figure 8). These deposits vary from conglomerate near the bordering mountains to mudstone near the basin center. Alluvial-fan materials interbedded with gravels near the axis along the Rio Grande unconformably overlie these deposits (Groat, 1972, p. 5). Thicknesses range from a minimum of 500 feet (152 m) to a maximum of 5,000 feet (1,524 m) along the axis. Wells located above the floodplain of the Rio Grande have small yields, but those in the proximity of the river have yields generally ranging from 300 to 800 gal/min (19 to 50 l/s) with some yielding as much as 2,000 gal/min (130 l/s). Two observation wells, located near Presidio and Redford respectively, have shown no significant change in water levels from 1966 to 1978.

Ground-water quality above the floodplain of the Rio Grande is usually fresh, but along the river it ranges from fresh to very saline with most of it being moderately saline. The overlying Rio Grande alluvium is usually less than 100 feet (30 m) thick and generally contains poor quality water.

The annual effective recharge was determined by using 1 percent of the mean annual precipitation on the outcrop area. The estimate, using this method, is 7,000 acre-feet or 8.63 hm^3 per year (Gates and others, 1978).

It is estimated that in 1976 there was about 1 million acre-feet (1,230 hm^3) of fresh to slightly saline ground water in storage in the Presidio and Redford Bolsons. Of this total, 800,000 acre-feet (986 hm^3) of fresh water was estimated to be in the Presidio Bolson. This estimate is based on the assumption that the average saturated thickness is 600 feet (183 m) and specific yield is 7.5 percent over an area of 29 square miles (75 km^2). Approximately 200,000 acre-feet (247 hm^3) of fresh to slightly saline ground water is estimated to be in storage in the Redford Bolson. This estimate is based on an average saturated thickness of 200 feet (61 m) and a specific yield of 10 percent over an area of 17 square miles or 44 km^2 (Gates and others, 1978). Of the total volume of fresh to slightly saline water in storage, it is estimated that 75 percent or 750,000 acre-feet (925 hm^3) can be recovered.

The average annual ground-water availability as shown in Appendix A was determined by dividing the quantity in recoverable storage by 54 years (January 1, 1976 through December 31, 2029) and adding the annual resultant depletion rate to the annual effective recharge.

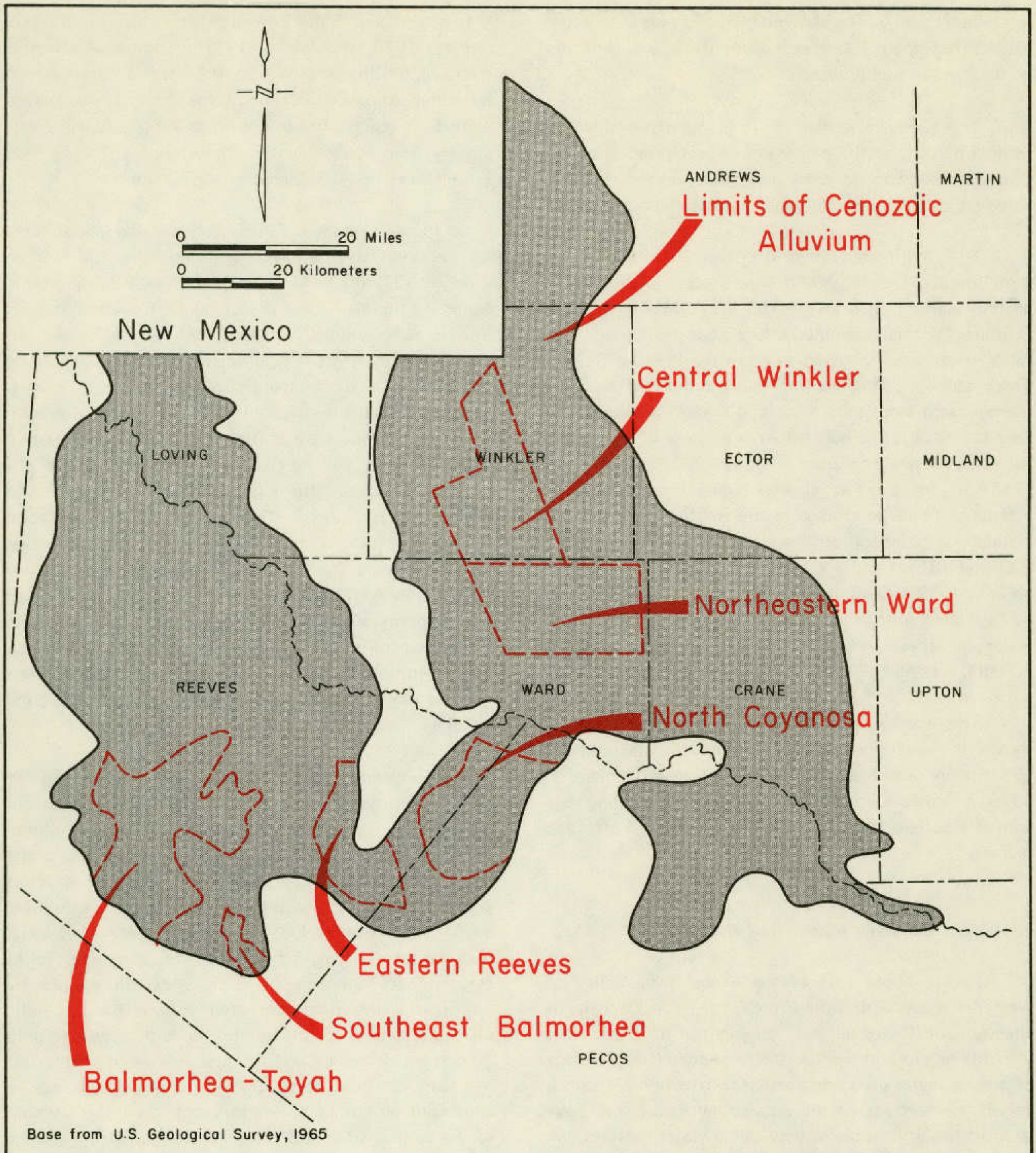
Cenozoic Alluvium of West Texas

In the upper part of the Pecos River Valley of West Texas and within the Rio Grande basin, deposits of alluvium of Cenozoic age ranging up to 1,500 feet (457 m) or more in thickness have yielded large volumes of ground water used principally for irrigation (Figures 6 and 9). In portions of the aquifer, gypseous soils have allowed the utilization of very saline water even though most of it contains between 1,000 and 4,000 mg/l of dissolved solids. The salinity of the ground water has increased in some of the heavily pumped areas; therefore, water quality may be a constraint on complete development of the recoverable water from the aquifer. Even so, a certain amount of ground water can be depended on as effective recharge.

The methodology used to determine the annual effective recharge for the Cenozoic Alluvium was based on an increase in base flow of 34,000 acre-feet (41.9 hm^3) along a segment of the Pecos River between the New Mexico State Line and Girvin (U.S. Geological Survey, 1918; and White, 1971). Additional effective recharge of 36,800 acre-feet (45.4 hm^3) per year was estimated using 60 percent of the Pecos River average annual diversions for irrigation as infiltration into the aquifer. Hence, the total annual effective recharge was estimated to be 70,800 acre-feet (87.3 hm^3).

In the Cenozoic Alluvium areas that are suitable for ground-water withdrawal, more than 30 million acre-feet (37,000 hm^3) of fresh to slightly saline ground water is estimated to be in storage. Of this amount, only about 9.48 million acre-feet (11,700 hm^3) can be withdrawn by wells if significant ground water quality degradation is to be avoided (Appendix A). The areas that are considered favorable for withdrawal of ground water from storage are central Winkler and northeastern Ward Counties, the north Coyanosa area of Pecos and Reeves Counties, the area in eastern Reeves and northwestern Pecos Counties, and the southeast Balmorhea and Balmorhea-Toyah areas of Reeves County (Figure 9). The geohydrological circumstances differ among these areas; therefore, the constraints placed upon ground-water development to restrict the movement of poor quality water varied accordingly. These limitations become evident in the subsequent explanation of the methods used to evaluate the ground water available from storage.

The evaluation of ground-water availability in Winkler and Ward Counties utilized pertinent data from reports by Garza and Wesselman (1959) and White (1971). The procedures used were: (a) to consider as the basic hydrologic parameter the areas containing predominately fresh ground water and to delineate these areas; (b) to determine the total volume of alluvial material saturated with fresh water in these areas; (c) to calculate the amount of fresh water in storage by multiplying the total saturated volume by a specific yield factor of 0.15; (d) to limit the withdrawals to only 30 percent of the total computed volume of fresh water in storage since water-quality deterioration was a constraint on complete development—thus, the estimate of the volume of ground water recoverable from storage amounted to 2.8 million acre-feet (3,450 hm^3) in central Winkler County and 3 million acre-feet (3,700 hm^3) in northeastern Ward County; (e) to divide the volume of water recoverable from storage by 53 years (1977 through 2029) to obtain an annual withdrawal rate under the assumption that water in storage would be extracted on a uniform annual basis to the year 2030; and finally (f) to add the annual depletion amount to the estimated annual effective recharge to give an estimate of the average annual ground-water availability to the year 2030.



Base from U.S. Geological Survey, 1965

Figure 9

Areas Suitable for Ground-Water Withdrawal from Storage in the Cenozoic Alluvium Aquifer of West Texas

As stated, it was estimated that only 30 percent of the total fresh water in storage could be removed without causing rapid degradation of the water quality caused by migration of undesirable ground water. This fresh water is suitable for most purposes and is surrounded by or adjacent to poor quality ground water that is either natural occurring or man induced. In some places the base of the fresh water lies at great depths—more than 800 feet (244 m) below land surface. Rapid and complete development of these fresh-water areas would result in water-level declines of over 800 feet (244 m) in many locations; consequently, it can be expected that poor quality water surrounding or below these areas would move quickly into the depleted zones due to the steep hydraulic gradients formed as fresh water is withdrawn. The proposed development of only 30 percent of the total fresh water in storage would cause water-level declines of approximately 300 feet (91 m). This level of decline is not considered great enough to cause excessive hydraulic gradients. Some water-quality deterioration would still occur, but the effects are thought to be minor with this level of development of the aquifer in these areas of Winkler and Ward Counties.

For Reeves and Pecos Counties, the procedural steps used to estimate the average annual quantity of ground water that is recoverable from storage were based on information obtained from reports on past works, namely: Rees and Buckner, 1979; Perkins and others, 1972; Ogilbee and others, 1962; and Armstrong and McMillion, 1961. Unlike the evaluation of the availability of ground water in Winkler and Ward Counties where delineation of the fresh-water area was the primary hydrologic parameter, in Reeves and Pecos Counties the geohydrologic characteristics are dissimilar and consequently required different parameters to delineate the areas suitable for ground-water withdrawals. Since withdrawals would be used primarily for irrigation in this particular area, the establishment of the hydrologic parameters was directed towards this end, that is: (a) a maximum of 3,000 mg/l dissolved solids in the ground water that would be considered for development, (b) a maximum percent sodium of 50, and (c) a maximum sodium-adsorption ratio (SAR) of 18.

Utilizing these ground water quality parameters and the above cited references, three maps were prepared depicting the ground-water quality in the Cenozoic Alluvium in Reeves and Pecos Counties. Next, a saturated thickness map covering the same area was constructed by superimposing a water-level map on a map of the base of the Cenozoic Alluvium. Making use of these maps, a composite map was prepared showing the ground-water quality parameters, saturated thickness, and the areas having arable soils. This composite map was then used to delineate the four areas considered suitable for irrigation with locally available ground-water supplies. These are the north Coyanosa, eastern Reeves, southeast Balmorhea, and Balmorhea-Toyah areas (Figure 9).

Within these delineated areas of contemplated ground-water development, the total volume of water in storage and the volume recoverable were obtained by using a planimeter on the saturated thickness intervals and multiplying by a specific yield of 10 percent. This specific yield was determined by comparing the total pumpage in Reeves County between 1951 and 1959 to the total volume of dewatered material.

The development of the recoverable water from storage in Reeves and Pecos Counties was limited by two primary concerns: (a) to maintain yields of irrigation wells at a minimum of 350 gal/min (22 l/s) and (b) to minimize water-quality deterioration. In order to accomplish these objectives in the north Coyanosa area, the quantity of water in recoverable storage of 656,900 acre-feet (810 hm^3) was calculated by assuming that 300 feet (91 m) of the saturated thickness would remain in storage. For the eastern Reeves area, where 1.28 million acre-feet (1,580 hm^3) was estimated to be in storage, only 50 percent was assumed recoverable. The quantity of recoverable storage was estimated to be 77,500 acre-feet (95.6 hm^3) in the southeast Balmorhea area where 300 feet (91 m) of saturated thickness was assumed to remain in storage. And finally, in the Balmorhea-Toyah area it was assumed that 300 feet (91 m) would be depleted; therefore, it was estimated that 1.67 million acre-feet (2,060 hm^3) was available as water recoverable from storage. Appendix A summarizes the average annual ground-water availability for the Cenozoic Alluvium under the assumption that water in storage would be withdrawn on a uniform annual basis between 1977 and 2030. Under this assumption, average annual available fresh water supply is the sum of estimated average annual effective recharge and the computed annual quantity of water recoverable from storage.

Alluviums of North-Central Texas

Scattered, isolated areas of alluvium (principally erosional remnants of the Seymour Formation) are sources of water supply for domestic, municipal, and irrigation needs of north-central Texas (Figure 6). These local aquifers which occur in parts of 22 north-central and panhandle counties in the upper Red and Brazos River basins vary greatly in thickness. In most areas, the saturated thickness is less than 100 feet (30 m). Yields of large-capacity wells range from less than 100 gal/min

(6.3 l/s) to as much as 1,300 gal/min (82 l/s). The average is about 300 gal/min (19 l/s). The quality of fresh to slightly saline water in these local aquifers differs widely from place to place but generally ranges from less than 500 mg/l to more than 2,500 mg/l of dissolved solids. The salinity has increased in many heavily pumped areas to the point that the water has become unsuitable for domestic and municipal use. Ground water in these areas also contains relatively high concentrations of nitrate which are considered to be undesirable for human consumption.

Annual effective recharge from the Alluvium aquifers of north-central Texas was determined principally by applying a percentage of the mean annual precipitation upon the aquifer's outcrop. This percentage was originally determined by application of the low-flow method of analysis which was used in the ground-water studies of Baylor and Jones Counties (Preston, 1978; and Price, 1978). On the basis of these studies, the current evaluation assumed 5 percent of the mean annual precipitation as effective recharge and estimated the total annual effective recharge of these aquifers to be 207,200 acre-feet (256 hm^3). A breakdown of this recharge by river basin and zone is shown in Appendix A.

It is estimated that in 1974 there was approximately 4.56 million acre-feet (5,620 hm^3) of fresh to slightly saline ground water in total storage in these scattered developments of alluvium. These estimates were made using the saturated thickness of the water-bearing alluvial deposits as determined, for the most part, from water-level observation well data and drillers' logs. Where data were sparce, a regional water-level map and a structure map at the base of the aquifers were constructed, and saturated thicknesses were estimated by overlaying the two maps. Geologic limits were delineated using the most recent geologic maps, and areas of recharge and ground-water storage were determined using a planimeter. The aquifer characteristics were depicted by tabulating all known alluvium aquifer pump tests and using a representative specific yield of 10 percent for the aquifer (Cronin, 1972; Maderak, 1973; Popkin, 1973a and b; Price, 1978 and 1979; and Smith, 1973).

Ground water recoverable from storage from these scattered alluvial aquifers was estimated to be 3.42 million acre-feet (4,220 hm^3) based on 75 percent of the total storage. Appendix A gives a breakdown of both the total and recoverable ground water in storage by river basin and zone.

Procedural steps used to determine the average ground-water availability shown in Appendix A were as follows: (a) the amount of ground water estimated to be recoverable from storage in all of the areas was divided by 56 years (January 1, 1974 through December 31, 2029) to determine an annual storage depletion rate, and (b) the annual storage depletion rate was added to the annual effective recharge for each of the areas to determine the average annual ground-water availability to the year 2030.

Leona Alluvium of Tom Green County

In east-central Tom Green County, along and south of the Concho River and east of San Angelo, are water-bearing deposits of alluvium which are part of the Leona Formation of Pleistocene age. On Figure 6, these sediments are included as part of the Alluvium and Bolson Deposits aquifer. They yield moderate volumes of ground water that is now used principally for irrigation.

Geological evidence shows that the Leona sediments were derived from the same source as the Ogallala Formation to the northwest and that these alluviums were deposited on an eroded surface of Permian rocks over an area of approximately 400 square miles (1,036 km^2). Since the time of deposition, streams have dissected the alluvium and it is now considered an effective aquifer only in the previously described area. Lithologically, the Leona is composed of discontinuous beds of poorly sorted, round to subangular gravel, conglomerate, sand, silty clay, and caliche (Willis, 1954). Total thickness of alluvium ranges from a few feet to about 125 feet (38 m).

Saturated thicknesses of these water-bearing rocks range from zero to a maximum of 117 feet (36 m). Yields to irrigation wells in the Wall-Veribest area generally range from about 100 gal/min (6.3 l/s) to nearly 7,000 gal/min (442 l/s). Water levels can rise rapidly following heavy rainfall. The chemical quality of ground water is suitable for most purposes and it usually ranges from fresh to slightly saline.

Ground water available from the Leona Alluvium on an annual basis was determined by a comparison of pumpage data and water-level trends. This aquifer was used as the example for this method as previously described under *Method of Study and Qualifications.* The annual effective recharge was estimated to be 8,000 acre-feet (9.86 hm^3) or approximately 4.6 percent of the mean annual precipitation between 1961 and 1975 on the area of effective recharge.

Water recoverable from storage was estimated to be 130,000 acre-feet (161 hm^3). This quantity was determined by calculating the volume of water in storage in the "zone to be depleted" using a grid spatial count and multiplying by a specific yield of 15 percent. The analysis depended upon leaving enough saturation in the aquifer to maintain transmissibilities of 10,000 (gal/d)/ft or 124,000 (l/d)/m.

Under the assumptions of this study, the average annual ground-water availability, as shown in Appendix A, was determined by dividing the volume of water in recoverable storage by 53 years (January 1, 1977 through December 31, 2029) and then adding this to the annual effective recharge.

Brazos River Alluvium of Southeast Texas

Another aquifer considered as part of the Alluvium and Bolson deposits is the water-bearing alluvium that occurs in the floodplain of the Brazos River of southeast Texas (Figure 6). These stream-deposited alluvial materials, which range from less than 1 mile (1.61 km) to about 7 miles (11 km) wide, supply comparatively large volumes of ground water used principally for irrigation. They extend approximately 350 miles (563 km) along the sinuous course of the river between northern McLennan County and central Fort Bend County (Cronin and Wilson, 1967).

An estimated 1,000 irrigation wells pump from this aquifer with most of the yields ranging from 250 to 500 gal/min (16 to 32 l/s). Saturated thickness of these deposits is as much as 85 feet (26 m) or more with the maximum thickness occurring in the central and southeastern part of the aquifer. The chemical quality of the ground water varies widely, even within short distances. In many areas, concentrations of dissolved solids exceed 1,000 mg/l. The soils of the Brazos River valley irrigated with this ground water are usually sufficiently permeable to alleviate soil salinity problems.

The methodology used to determine the annual effective recharge to this aquifer was principally the comparison of water-level trends and pumpage. On this basis, the total annual effective recharge to the Brazos River alluvium was estimated to be 100,000 acre-feet or 123 hm^3 (Cronin and Wilson, 1967, p. 73). A breakdown of this recharge by zone is shown in Appendix A.

Using data prepared by Cronin and Wilson (1967, p. 73), approximately 1.85 million acre-feet (2,280 hm^3) of fresh to slightly saline ground water was estimated to be in storage in the areas considered. Based on 75 percent of the total storage, approximately 1.38 million acre-feet (1,710 hm^3) is estimated as water recoverable from storage.

The average annual ground-water availability to the year 2030 as shown in Appendix A was calculated by dividing the estimated recoverable storage by 56 years (January 1, 1974 through December 31, 2029) to determine the annual storage depletion rate and then adding this to the annual effective recharge.

In summary, the total estimated annual effective recharge to the Alluvium and Bolson Deposits aquifer in Texas, is 434,000 acre-feet (535 hm^3). This is an increase of 121,200 acre-feet (149 hm^3) or 39 percent over the estimate in the 1968 Texas Water Plan. Due to constraints placed upon the Cenozoic Alluvium to prevent water-quality deterioration, complete development of all the ground water in storage in this aquifer is not feasible and therefore an estimate of total quantity in storage for all of the alluvium and bolsons evaluated throughout the State was not made. About 32.7 million acre-feet (40,300 hm^3), however, is estimated to be recoverable. This is an increase of about 22.9 million acre-feet (28,200 hm^3) or 335 percent over the estimate in the 1968 Texas Water Plan. All increases are due to the inclusion of areas which were not evaluated for the 1968 Plan.

Gulf Coast

Geologically, the Gulf Coast aquifer ranges in age from Miocene to Holocene and, for the purposes of this report, it is considered as composed of the Catahoula, Oakville, Lagarto, Goliad, Willis, Lissie, and Beaumont Formations, as well as overlying surficial deposits. The aquifer consists of alternating beds of clay, silt, sand, and gravel which are hydrologically connected and form a large, leaky artesian aquifer system. Its principal water-bearing units are the Goliad, Willis, and Lissie Formations. The areal extent of the aquifer is shown on Figure 6, and Appendix B lists the water-bearing properties.

Normally, water of better quality, that is, less than 500 mg/l dissolved solids, occurs in the aquifer from the San Antonio River basin northeastward to Louisiana. In this area, usable quality water may be encountered to a maximum depth of 3,200 feet (975 m) below land surface. The maximum total aggregate sand thickness is about 1,300 feet (396 m). Well yields in this portion of the aquifer usually average about 1,600 gal/min (101 l/s). Larger quantities, up to 4,500 gal/min (284 l/s), of fresh to slightly saline water are pumped by some individual wells for municipal, industrial, and irrigation use. However, there are areas in southeastern Chambers and Jefferson Counties where no appreciable amounts of fresh to slightly saline ground water can be found.

Ground-water quality tends to deteriorate in the San Antonio River basin and southwestward to Mexico, mainly because of an increase in the chloride content. The concentration of dissolved solids in this portion of the aquifer is generally between 1,000 and 1,500 mg/l and there are areas in Aransas, Calhoun, Cameron, Hidalgo, Kenedy, Kleberg, Nueces, San Patricio, and Willacy Counties where no appreciable amounts of fresh to slightly saline ground water can be found. On gulf-shore islands, ground water suitable for domestic and livestock requirements may be found in shallow sands. Little of the water in this part of the aquifer is acceptable for prolonged irrigation use due to either high salinity or alkalinity hazard, or both. In the Lower Rio Grande Valley, supplemental ground water is pumped from the Gulf Coast aquifer for irrigation as well as for municipal use during times when the Rio Grande does not meet demands. In this area between the San Antonio River basin and Mexico, the maximum depth of the aquifer below land surface is 2,800 feet (853 m), and the maximum total sand thickness is about 700 feet (213 m).

Problems related to withdrawal of ground water from the Gulf Coast aquifer are: (a) land-surface subsidence, (b) increased chloride content in the ground water of the southwest portion of the aquifer, and (c) salt-water encroachment along the coast. Each of these received consideration in the long-term regional water-supply estimates of this aquifer.

Methodology

Evaluation of the long-term regional water-supply capabilities of the Gulf Coast aquifer was accomplished by utilizing the trough method which was incorporated into a digital computer model of the aquifer that simulates leaky artesian conditions. The use of this model allowed for the simulation of pumpage, simulation of associated water-level declines, and simulation of land-surface subsidence, and consequently provided a means to evaluate the ability of the aquifer to meet future ground-water requirements. A detailed description of the assumptions, construction, verification, application and use, and results of the model follows.

Assumptions

In simulating the Gulf Coast aquifer with the computer model, the major assumption was that the entire Gulf Coast aquifer has similar geology and that its composite section is one of leaky artesian conditions. Leaky artesian conditions exist when aquifers are overlain by confining beds or aquitards which impede the vertical flow. Moreover, it was assumed that the leakage through the aquitards into the aquifer is vertical and proportional to the difference in the head between the source bed above the confining layer and the aquifer. Other assumptions were that the hydrostatic head remains constant in the source bed, that the storage in the confining bed can be neglected, and that the head in the aquifer does not fall below the bottom of the confining layer.

Jorgensen (1975, p. 55) established in his hydrologic budget study of the Houston area that approximately 90 percent of the ground water developed from the aquifer was derived locally from a leaky artesian system; therefore, it was assumed that most of the ground water supplied to the system was derived from a local source. In this system, the sources of water came from vertical leakage as recharge from the land surface (precipitation, lakes, rivers, streams, and applied irrigation water), compaction of clays, depletion of artesian storage, vertical leakage from beds above or below the aquifer, and lateral inflows from adjacent areas.

When water is pumped from a leaky artesian system such as the Gulf Coast aquifer, the hydrostatic pressure is decreased in the water-bearing sands and water moves from the adjacent clays with higher pressure into the sands in response to the pressure difference. Compaction occurs in the fine-grained sediments or clays as water is released with a corresponding decrease in hydrostatic pressure. This reduction in the volume of clay results in subsidence at the land surface. Compaction in clay beds may also occur when an aquifer is under water-table conditions where there is a declining hydrostatic head. Compaction in this case is due to an increased load which results from the loss of buoyancy of the aquifer material as the water table is lowered.

Jorgensen (1975, p. 49) stated that "the volume of water derived from compaction of clay is very nearly equal to the volume of subsidence in the Houston district because nearly all subsidence is related to ground-water pumpage from the Chicot and Evangeline aquifers." These aquifers are included in the Gulf Coast aquifer. The Chicot is equivalent to the Willis, Lissie, and Beaumont Formations and the Evangeline is equivalent to the Goliad Formation. Using this criterion, ground-water pumpage was assumed to be the primary cause of land-surface subsidence due to the compaction of the water-bearing clays. Admittedly, some subsidence was caused by the removal of hydrocarbons such as near Corpus Christi and in areas southeast of Houston.

Relationships between land-surface subsidence, the decline in the potentiometric surface, and the percentage of clay above the deepest producing aquifers were discussed by Gabrysch (1969). Winslow and Wood (1959, p. 1034) determined that approximately 22 percent of the ground water pumped from the Gulf Coast aquifer in the Houston vicinity was derived from the clays. Additional data assembled on the same area by Jorgensen (1975, p. 49) also verified this percentage.

Recently, personnel of the U.S. Geological Survey at Houston conducted soil and sample tests on a test well at Seabrook. Using these data, they estimated the average specific-unit compaction value for the clay. The estimate was 3.1×10^{-5} foot^{-1} (9.45×10^{-6} meter^{-1}); that is, for every foot of water-level decline in the sample data each foot of dewatered clay is estimated to compact 0.000031 foot or 0.0000094 meter (Gabrysch and Bonnet, 1975, p. 15). It was first assumed that this average specific-unit compaction value applied to the clays of the entire Gulf Coast, the thickness of which was determined from electric logs and was incorporated into the model; however, recent releveling data assembled by the Texas Water Development Board during 1976 and 1977 in the Kingsville area indicate that the average specific-unit compaction value for clay may be somewhat less in the southern part of the aquifer. Based on these findings, adjustments were made in the model for the area south of the Lavaca River basin and the Lavaca-Guadalupe Coastal basin to account for this difference. As additional work is conducted, the subsequent data from test holes and detailed sample studies of the clays of the entire region will provide a more refined subsidence estimate for future planning.

Recent investigations by the Bureau of Economic Geology, The University of Texas at Austin, indicate that ground-water and hydrocarbon withdrawals in portions of the coastal zone may have caused increased fault activation (Brown and others, 1974, p. 11). It was asserted that nearly all faulting occurred in areas where the potentiometric surface has been lowered over 100 feet (30 m) and where there has been at least 1 foot (0.3 m) of land-surface subsidence. This is not to imply that in every case where there are water-level declines and land-surface subsidence of this magnitude there will be fault activation; however, in areas where there is significant ground-water withdrawals associated with land-surface subsidence, in general, there is fault activation.

Based on the observations within the Bureau of Economic Geology's study area, the somewhat arbitrary 100 feet (30 m) of water-level decline and its associated land-surface subsidence were assumed to be reasonable limits for use in aquifer simulation.

The simulated conditions of pumpage (discussed later, under the heading "Application and Use Phase") used to evaluate the ground-water availability of the Gulf Coast aquifer utilized the Bureau's observations and limited water-level declines to 100 feet (30 m) and land-surface subsidence to 1 foot (0.3 m) which should minimize possible fault activation.

Construction of the Model[1]

The region modeled was segmented into a rectangular array of 1,210 subareas called cells. Each cell was sized at 10 miles (16.1 km) by 10 miles, or 100 square miles (259 km^2). Of the total cells, 615 were active and were used to simulate the aquifer in all or parts of 53 counties. These were of two types, leaky artesian and boundary cells. The remaining 595 cells did not overlie the aquifer and therefore were not included in the simulation process. Seven geologic and hydrologic parameters were programmed into each cell. These parameters were the coefficient of transmissibility, coefficient of storage, initial heads in the aquifer, initial heads in the source beds, a recharge factor which governed the rate of leakage through the confining beds, total clay thickness in the saturated zone containing fresh to slightly saline water, and pumpage.

Verification of the Model

Three areas were selected to be studied and simulated in the limited verification phase of the modeling. These were the Houston, Jackson-Wharton Counties, and Kingsville areas. Their selection was based upon three factors: (a) the need to economize time because the total Gulf Coast region was so vast; (b) geographical locations to be representative of the entire region; and (c) the availability of data related to pumpage, subsidence, and declining water levels. The first series of model verification analyses involved pumpage, water-level drawdowns, and subsidence data for the 10-year period 1960 through 1969. The objective of these model analyses was to input the data of initial heads, pumpage, and related information for this period

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[1] Hydrologic computer techniques used in the construction of the model initially were developed by Prickett and Lonnquist (1971, p. 31-33). William B. Klemt proposed the incorporation of subsidence capabilities into the model. Modifications of the original model were completed by Tommy R. Knowles. Robert D. Price developed the geologic and hydrologic data for model verifications and operated the model to develop and organize the final interpretative results.

and compare the resultant computed water-level declines and subsidence to the historical water-level declines and subsidence. Adjustments were made to the input data (clay thickness and recharge factors) in order that the model could simultaneously simulate water levels and subsidence within reasonable limits. The following table gives the amounts by which the computed heads deviated from the observed historical heads.

Area	Difference between observed and computed heads (feet and meters)
Houston	+2.12 (+0.65 m)
Jackson-Wharton Counties	−0.48 (−0.15 m)
Kingsville	+0.18 (+0.05 m)

The computed subsidence was in acceptable agreement with known subsidence for the model verification period 1960 through 1969. The average error for the Houston area was -0.25 foot (-0.08 m). In Jackson-Wharton Counties, the model simulated 0.1 to 0.6 foot (0.03 to 0.18 m) of subsidence which compares favorably with the total known subsidence of up to 1.0 foot or 0.305 m (Brown and others, 1974). The model originally simulated a maximum of 0.5 foot (0.2 m) of subsidence (1960 through 1969) for the Kingsville area which was not in very good agreement with the estimated subsidence of 0.298 foot (0.091 m) for the period 1917 through 1976. Adjustments were made to the model in the lower Gulf Coast region to reflect these findings.

It is re-emphasized that the model was verified only in the areas previously discussed and that data derived from these areas were then applied to the whole Gulf Coast region.

Application and Use Phase

In this phase of the study, the model computed the annual ground-water availability using a 50-year period (1970 to 2020) with the following simulated conditions of pumpage and other constraints: (a) pumpage was selectively assigned to certain model cells inorder that water levels could be lowered approximately 100 feet (30 m) along a theoretical line of discharge lying approximately midway between the center line of the outcrop and the freshwater and saltwater interface of the Gulf Coast aquifer, (b) declines of the hydraulic head at the freshwater and saltwater interface were minimized, and (c) water-level declines in existing cones of depression greater than 100 feet (30 m) were halted by a reduction of pumpage.

In order to have better agreement between the availability data derived from the Department's model and investigations by the U.S. Geological Survey (Gabrysch, 1977; and Jorgensen, 1975), adjustments were made within the Houston district, which is comprised of Harris County and portions of the surrounding counties. Gabrysch (1977, p. 38) stated that "the decrease in the rates of water-level declines suggests that the aquifers in the Houston district could support almost as much production as in 1970-74 (about 500 million gal/d or 21.9 m^3/s) with little, if any, further decline in water levels." However, subsidence would continue for a period of time after water levels stabilized. A total annual effective recharge of 350 million gal/d (1,300 million l/d) for the district was agreed upon by representatives of the Department and U.S. Geological Survey. This would allow water levels to rise and subsidence to cease after a year or two. Of this amount, Harris County was assigned 250 million gal/d (950 million l/d) and Galveston County was assigned 19.6 million gal/d (74 million l/d). The remainder, or 80.4 million gal/d (300 million l/d), was distributed among the remaining counties within the Houston district (Gabrysch, 1977, Figure 5). This adjustment increased the annual effective recharge in the Houston area by 7,000 acre-feet (8.63 hm^3) or about 9 percent more than originally determined by the Department's digital model.

Results of the Idealized Model Runs

Using the previously mentioned simulated conditions of pumpage and other restraints, the computer model studies indicate that the Gulf Coast aquifer system will approach steady-state conditions after 20 years. The Houston area is presently approaching steady-state conditions (Gabrysch, 1977, p. 38). Therefore, the ground-water availability computed by the model, plus the adjustments made in the Houston area based on recent U.S. Geological Survey investigations, represents a perpetual annual effective recharge of 1.23 million acre-feet (1,520 hm^3). This is a 48 percent decrease from the 1968 availability estimate. A tabulation of the ground-water availability by river or coastal basin, zone, and aquifer is given in Appendix A.

This analysis indicates that subsidence should stabilize in areas other than around Houston after about 20 to 25 years or around the year 1990 as water levels cease to decline when the system reaches equilibrium. Data in the vicinity of Houston indicate that subsidence in that area is presently stabilizing. Maximum land-surface subsidence as computed for the simulated conditions of pumpage is 2.3 feet (0.7 m). Figure 10 shows the land-surface subsidence distribution resulting

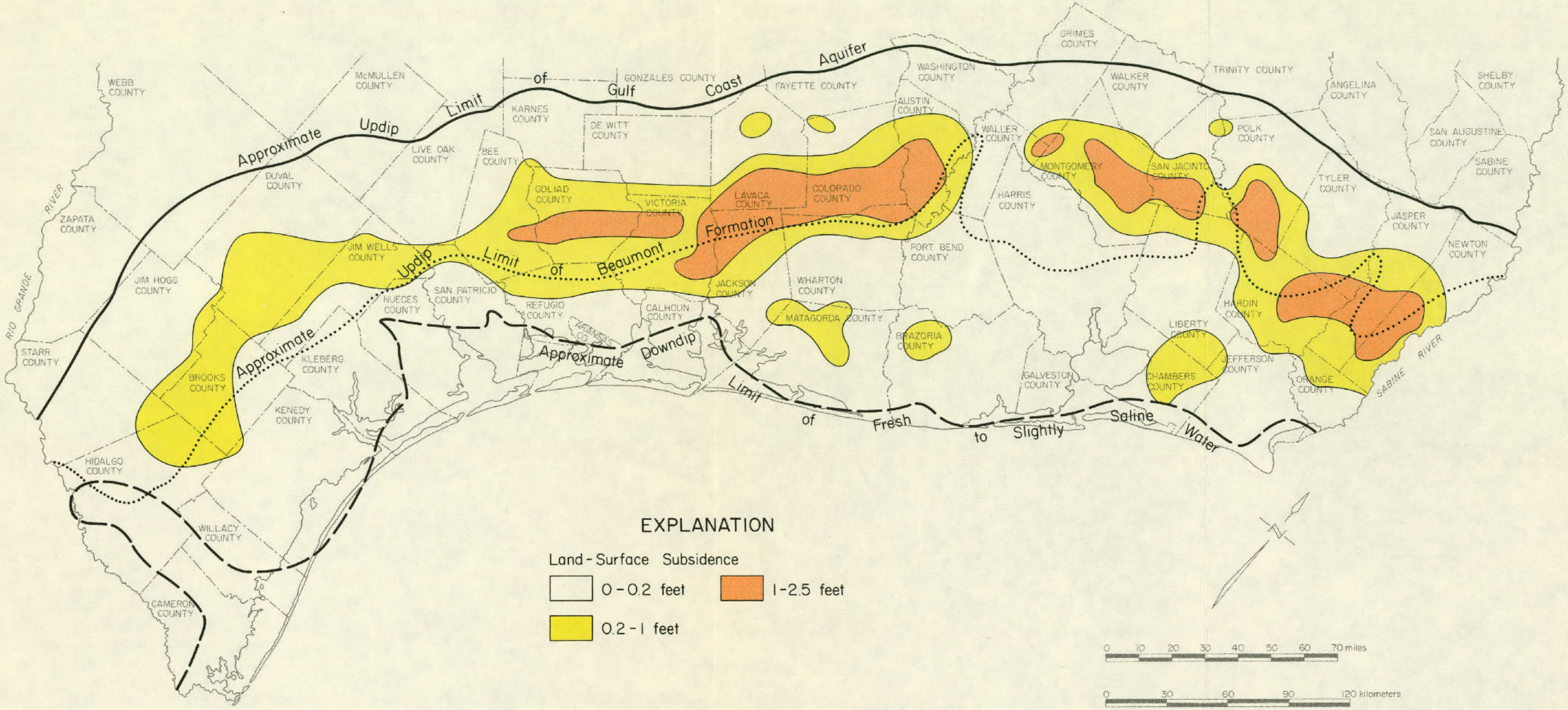


Figure 10

Simulated Land-Surface Subsidence in the Gulf Coast Aquifer, 1970 to 2020

Base from U.S. Geological Survey, 1965

from the analysis. The total resulting subsidence (known subsidence plus the subsidence under the assumed conditions of pumpage) would reach a maximum of about 8.5 feet (2.6 m) which now exists in the Houston area. The total subsidence distribution is shown on Figure 11.

It is estimated that about 4 percent of the mean annual rainfall on the outcrop of the aquifer would be necessary to support the estimated annual effective recharge to the aquifer.

Edwards-Trinity (Plateau)

The Edwards-Trinity (Plateau) aquifer underlies the Edwards Plateau east of the Pecos River and the Stockton Plateau west of the Pecos River. Its geographic limits extend from Gillespie County on the east to Culberson County in the Trans-Pecos area on the west, and from Kinney County on the south to Howard County on the north (Figure 6). It lies predominantly in the Rio Grande and Colorado River basins with its extreme southeastern boundaries extending into the Nueces, San Antonio, and Guadalupe River basins. The aquifer consists of saturated sediments of Lower Cretaceous age made up of sands, sandstone, gravel, and conglomerate of the Trinity Group (Antlers Formation); and cherty, gypseous, argillaceous, cavernous limestones and dolomites of the Comanche Peak and Edwards Limestones and the Georgetown Formation. The Santa Rosa Sandstone of Triassic age is also included in the aquifer where it underlies and is in hydrologic continuity with the Cretaceous rocks.

The maximum saturated thickness of these water-bearing rocks is more than 800 feet or 244 m (Walker, 1979). The ground water generally flows in a southeasterly direction conforming to the dip of the beds. Near the edge of the Plateau, movement is toward the main streams where ground water issues from springs. Some of the large-capacity wells completed in jointed and cavernous limestone can yield as much as 3,000 gal/min (189 l/s).

Chemical quality of Edwards-Trinity (Plateau) water ranges from fresh to slightly saline. The water is generally hard and may vary widely in concentrations of dissolved solids made up mostly of calcium, magnesium, and bicarbonate. The salinity of the ground water generally increases toward the west. Occasionally, certain areas may have unacceptable levels of fluoride.

The quantities of ground water available from the Edwards-Trinity (Plateau) aquifer are given in terms of annual effective recharge in Appendix A. These quantities were determined by evaluating the historical base flows and spring flows in the two main river basins in which the aquifer lies, namely the Rio Grande and Colorado River basins (Brune 1975; and Grozier and others, 1966). Spring discharges from the aquifer into the Nueces, San Antonio, and Guadalupe River basins eventually become recharge to the Edwards (Balcones Fault Zone) aquifer; therefore, these quantities are part of the effective recharge for the Edwards (Balcones Fault Zone) aquifer.

Regarding the evaluation of the Edwards-Trinity (Plateau) aquifer in the Colorado River basin, spring flows are nonexistent along the northern edge of the Plateau between Ector and Coke Counties. This indicates that consumptive use (evapotranspiration and pumpage) exceeds the effective recharge in this area. However, it was possible to evaluate the historical spring flows discharging into the Concho, San Saba, Llano, and Pedernales Rivers which are in the Colorado River basin (Brune, 1975). The annual effective recharge for the aquifer in the Colorado River basin was calculated to be 262,100 acre-feet (323 hm^3).

In the Rio Grande basin, the spring flows from the Edwards-Trinity (Plateau) aquifer have been measured historically on the Rio Grande, Pecos, and Devils Rivers (Brune, 1975; and Reeves, 1973). These were evaluated and the average annual ground-water availability was found to be 513,900 acre-feet (634 hm^3).

Based on the measurements of base flows and spring discharges in the Edwards and Stockton Plateaus as outlined above, the Edwards-Trinity (Plateau) aquifer has a total annual effective recharge of 776,000 acre-feet (957 hm^3). This is an increase of 118,000 acre-feet (146 hm^3) or 18 percent over the quantity estimated in 1968 which had been determined by using a percentage of the rainfall as annual effective recharge.

In the northwestern part of the Edwards Plateau and in the Stockton Plateau, the quantity of ground water in storage was determined for only the Trinity Group (Antlers Formation) and the Santa Rosa Sandstone where it underlies and is in hydrologic continuity with Cretaceous rocks. The volume of these saturated sediments was determined and multiplied by a coefficient of storage of 0.086 which was derived from aquifer test data (Walker, 1979). In the southeastern portion of the Edwards Plateau, the Trinity Group is not an effective aquifer; however, the volume of the saturated rocks of the Edwards and associated limestones, an effective aquifer, was determined from available maps of saturated thickness and then multiplied by an approximate specific yield value of 0.04. This approximate value is a conservative estimate

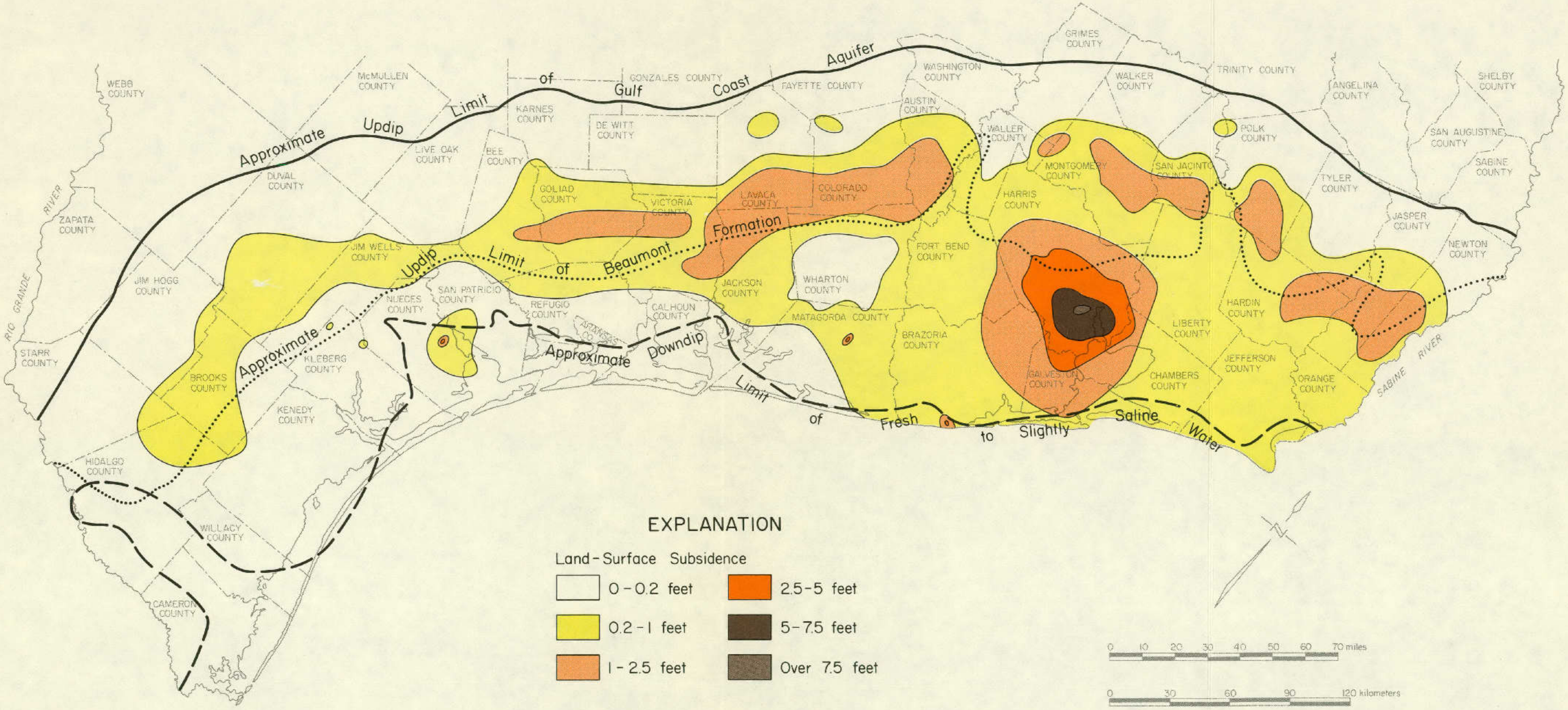


Figure 11

Total Land-Surface Subsidence in the Gulf Coast Region, 1906 to 2020 (Actual and Simulated)

Base from U.S. Geological Survey, 1965

of effective porosity. It is based on aquifer test results on the Edwards and associated limestones in the San Antonio area (Sieh, 1975, p. 36). The total quantity of water in storage for the Edwards-Trinity (Plateau) aquifer as given in Appendix A is about 194 million acre-feet (239,000 hm^3) and the quantity recoverable from storage is about 145 million acre-feet (179,000 hm^3); however, neither of these amounts of ground water is considered developable. There are two reasons for this. First, extensive withdrawals from storage would deplete available surface-water supplies and adversely affect natural recharge to the Edwards (Balcones Fault Zone) aquifer; and second, the aquifer extends over a broad area, is heterogeneous and anisotropic, and therefore is difficult to evaluate with regard to potential dependable development.

Minor Aquifers

The minor aquifers in Texas are important and in some areas are the only sources of water supply. Minor aquifers are defined as those which yield large quantities of water in small areas or relatively small quantities of water in large areas of the State. These aquifers are essentially the same as the minor aquifers described in the 1968 Texas Water Plan, although a few more have been delineated and added to this evaluation. Their locations and extent are shown on Figure 12. Their ground-water availabilities are summarized in Table 1 and Appendix A. Water-bearing properties of the minor aquifers are described in Appendix B. A description of the minor aquifers and the availability of ground water derived from each follows.

Woodbine

Water occurring in sand and sandstone beds of the Woodbine aquifer of Cretaceous age furnishes municipal, industrial, and small irrigation supplies throughout an extensive area of the State from northern McLennan County northward to the Red River. The aquifer is exposed at the surface in a narrow belt which trends south from southeastern Cooke County to McLennan County. The Woodbine aquifer dips eastward into the subsurface of northeast Texas where it reaches a maximum thickness of about 600 feet (183 m) and has a maximum depth of 2,000 feet (610 m) below land surface (Peckham and others, 1968).

Yields of wells completed in the Woodbine aquifer range from less than 100 gal/min (6 l/s) to about 700 gal/min (44 l/s). The water is principally a sodium bicarbonate type that is generally high in dissolved solids; sulfate, fluoride, and in places, chloride. Poorer quality water containing excessive iron concentrations is usually encountered in the upper water-bearing sands of the Woodbine. In most cases, only the lower part of the aquifer is developed to supply domestic and municipal wells.

The amount of ground water available from the Woodbine aquifer was determined by finding the transmission capacity of the aquifer. This was done by using the trough method in which the water levels were lowered 400 feet (122 m) below land surface along a hypothetical line of discharge. The average annual ground-water availability was found to be 26,100 acre-feet (32.2 hm^3), which is 1,000 acre-feet (1.23 hm^3) or 4 percent more than the 1968 estimate. Less than 1 inch (2.54 cm) of average annual precipitation is required as effective recharge in the outcrop area to supply the potential withdrawal.

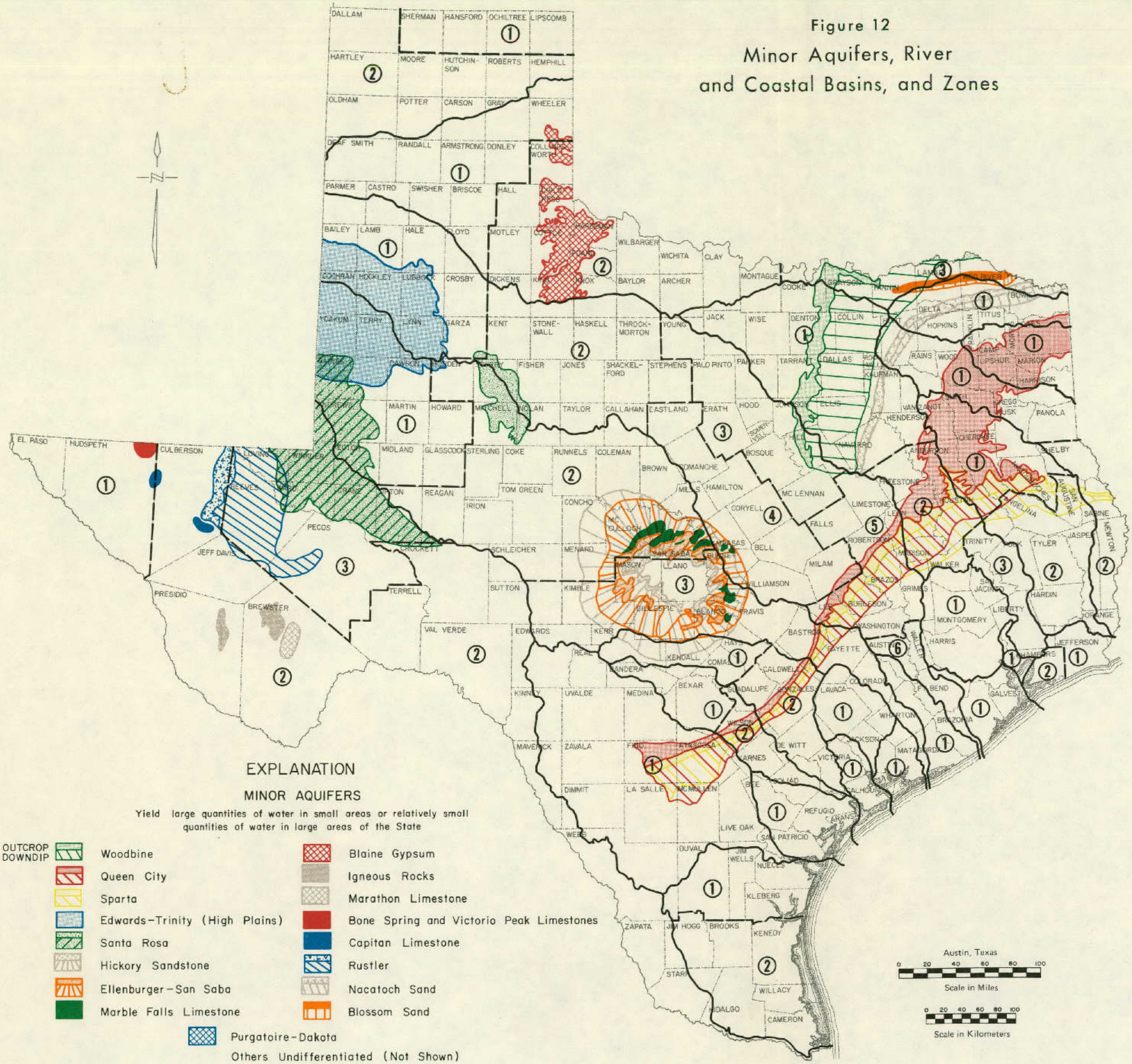
Queen City

The Queen City aquifer of Eocene age extends from the Frio River in Frio County northeastward into the Sulphur River basin. The aquifer consists principally of sand, loosely cemented sandstone, and interbedded clays which are as much as 500 feet (152 m) thick. The Queen City aquifer is exposed at the surface throughout much of its extent in northeast Texas and dips gently toward the southeast beneath younger formations.

Yields of wells are generally low with only a few exceeding 400 gal/min (25 l/s). Concentrations of dissolved solids are generally low. However, throughout parts of the aquifer in northeast Texas, the ground water has high acidity (low pH) and locally contains excessive concentrations of iron. Hydrogen sulfide also is encountered in wells in some areas. Ground water containing less than 3,000 mg/l extends to depths of approximately 2,000 feet (610 m) below the land surface (Peckham and others, 1968).

Water availability from the Queen City aquifer in the Trinity, Colorado, Guadalupe, San Antonio, and Nueces River basins is based on assumed pumpage conditions and is related primarily to the ability of the aquifer to transmit water (recharge) to areas of pumpage (Peckham and others, 1968). Because the transmissibility of the Queen City is low, the aquifer is not able to transmit large quantities of water. Therefore, in order to supply the water which the aquifer is capable of transmitting, less than 2 percent of the average annual rainfall in the above river basins is required as effective recharge on the outcrop.

Figure 12
Minor Aquifers, River and Coastal Basins, and Zones



EXPLANATION

MINOR AQUIFERS

Yield large quantities of water in small areas or relatively small quantities of water in large areas of the State

OUTCROP ▨ DOWNDIP ▧

▨ Woodbine
▨ Queen City
▨ Sparta
▨ Edwards–Trinity (High Plains)
▨ Santa Rosa
▨ Hickory Sandstone
▨ Ellenburger–San Saba
■ Marble Falls Limestone
▨ Blaine Gypsum
■ Igneous Rocks
▨ Marathon Limestone
■ Bone Spring and Victorio Peak Limestones
■ Capitan Limestone
▨ Rustler
▨ Nacatoch Sand
▨ Blossom Sand
▨ Purgatoire–Dakota
Others Undifferentiated (Not Shown)

——— River or coastal basin boundary
— — — Zone boundary
⑤ Zone number

Austin, Texas

0 20 40 60 80 100
Scale in Miles

0 20 40 60 80 100
Scale in Kilometers

In the Neches, Sulphur, and Sabine River basins and the Cypress Creek basin where the aquifer outcrops over extensive areas, the availability of ground water was determined by applying 5 percent of the average annual rainfall on the outcrop. The resulting estimate of average annual ground-water availability for the Queen City is 682,100 acre-feet (841 hm^3). This represents a large increase over the availability shown in the 1968 Texas Water Plan because the outcrop area of the aquifer on the western and northwestern flanks of the Sabine Uplift was not included in the 1968 evaluation.

Sparta

The Sparta aquifer, also of Eocene age, extends from the Frio River in Frio County northeastward to the Texas-Louisiana State line at the east edge of Sabine County. The Sparta aquifer is composed mainly of sands and interbedded clays which dip south and southeast from the outcrop area. It ranges in thickness from 100 feet (30 m) to approximately 300 feet (91 m).

Large-capacity wells, producing principally from thick sand beds near the base of the formation in the northern extension, generally yield 400 to 500 gal/min (25 to 32 l/s). Ground water produced from the aquifer is generally low in concentrations of dissolved solids; however, in many areas the aquifer contains iron in excess of proposed U.S. Environmental Protection Agency secondary standards. Along the southeastern boundary of the aquifer, slightly saline water can be found to depths of more than 2,000 feet (610 m) below the land surface (Peckham and others, 1968).

The ground-water availability estimate of the Sparta aquifer is based on assumed pumpage conditions that are related primarily to the ability of the aquifer to transmit water (recharge) from the outcrop to discharge areas downdip. This is an application of the trough method (Peckham and others, 1968). However, in the Sabine and Neches River basins where the ground-water availability had not previously been determined by the trough method, the calculated availability from the Trinity River basin southwestward to the Frio River was translated into terms of a percentage of the average annual rainfall, and this amount was applied to the outcrop area as effective recharge. Approximately 5 percent of the average annual precipitation received on the outcrop as effective recharge can be transmitted downdip by the aquifer for development. Using the above methods, the average annual ground-water availability for the Sparta was found to be 163,800 acre-feet (202 hm^3) or 78 percent more than estimated in the 1968 Texas Water Plan.

Edwards-Trinity (High Plains)

Sands and sandstones of the Trinity Group and limestones of the Fredericksburg Group make up this aquifer which has a varying total thickness of as much as 300 feet (91 m). It underlies, and is generally in hydrologic contact with, the Ogallala Formation in much of the southern High Plains (Cronin and others, 1963; and Mount and others, 1967). Yields are generally small except where water is present in the limestone. In this case, yields range up to 600 gal/min (38 l/s). The water quality is usually poorer than that in the overlying Ogallala aquifer and is usually slightly to moderately saline. Small quantities of water are produced from the aquifer for irrigation and secondary oil recovery.

The amount of ground water recoverable from storage was estimated to be approximately 1 million acre-feet (1,230 hm^3) and, in this report, is included with the availability from the Ogallala aquifer Table 1 and Appendix A. This estimate of storage was derived by assuming that the average saturated sand thickness of the Trinity Group was 30 feet (9 m) with a specific yield of 0.15, and that the average saturated thickness of the Edwards and associated limestones was 20 feet (6 m) with a specific yield of about 0.015 (Mount and others, 1967). The above figure for the ground water available from storage had been reduced considerably because of poor ground-water quality in a 250-square-mile (647-km^2) area in the eastern portion of the aquifer.

Santa Rosa

The Santa Rosa Formation of Triassic age consists principally of interbedded shale, sand, sandstone, and conglomerate. It underlies the Ogallala aquifer in many areas in the High Plains and is exposed at the land surface east of the caprock edge or escarpment. It also underlies the alluvium in the middle Pecos River basin and forms a subcrop band underlying the western part of the Edwards Plateau trending northeastward from Crockett County to Sterling County. Saturated thickness of the aquifer may be as much as 700 feet (213 m) in the portions underlying the plateau. Yields of wells vary and do not normally exceed 300 gal/min (19 l/s).

Concentrations of dissolved solids in the ground water range from less than 100 mg/l to more than 4,000 mg/l in the west where the aquifer has been developed for domestic and livestock uses and for oil field water-flooding operations. Although the water is usually comparatively low in dissolved solids, the sodium content is high, thus limiting long-term use of the water for irrigation.

Availability of water from the Santa Rosa aquifer was determined by comparing pumpage and water-level trends in Mitchell and Nolan Counties for the period from 1957 to 1964 (Cronin and others, 1963, p. 58; Mount and others, 1967, p. 56-57; and Shamburger, 1967, p. 66-71). Using this method, an estimated annual effective recharge of 23,500 acre-feet (29.0 hm^3) is obtained. This represents a decrease of 9,900 acre-feet (12.2 hm^3) or 30 percent less than the amount in the 1968 Texas Water Plan. Ground-water storage in the Santa Rosa aquifer underlying the Cretaceous rocks is included in the availability figures for the Edwards-Trinity (Plateau) aquifer.

Hickory Sandstone

The Hickory Sandstone aquifer underlies the Ellenburger-San Saba aquifer in the Llano Uplift region of central Texas and presently furnishes most of the ground water used in this area (Figure 6). The aquifer is made up principally of sand and sandstone of the Hickory Sandstone Member of the Riley Formation of Cambrian age. These are the most ancient water-bearing rocks evaluated in this report. Maximum thickness of the Hickory is about 500 feet (152 m). The aquifer is extensively faulted, and its beds dip steeply away from the Llano Uplift.

Yields of wells completed in the aquifer generally range between 200 and 500 gal/min (13 to 32 l/s) although a few wells have yielded more than 1,000 gal/min (63 l/s).

Dissolved-solids concentrations of water pumped from the aquifer commonly range from about 300 to 500 mg/l. However, ground water containing less than 3,000 mg/l dissolved solids extends to maximum depths of about 5,000 feet (1,524 m) below the land surface as far west as the Concho-Tom Green County line.

The current estimate of annual effective recharge is 52,600 acre-feet (64.9 hm^3), which is 7,600 acre-feet (9.37 hm^3) or 17 percent more than the 1968 amount. Previous estimates of availability from the Hickory Sandstone aquifer were obtained by comparing water levels with pumpage (Mason, 1961; Mount and others, 1967; and Peckham, 1967). Using data presented by Mason (1961, p. 27) in McCulloch County, the effective recharge was estimated to be approximately equal to the pumpage, and it was further determined that the effective recharge was equal to approximately 10 percent of the mean annual precipitation. The current appraisal uses 10 percent of the mean annual precipitation as the estimate of effective recharge. Also, a more precise estimate of the outcrop area was made by planimeter.

Ellenburger-San Saba

The Ellenburger-San Saba aquifer, composed of limestone and dolomite of the San Saba Member of the Wilberns Formation of Cambrian age and the Ellenburger Group of Cambrian and Ordovician age, yields small to moderate supplies of water for domestic, municipal, industrial, and minor irrigation needs in the middle Colorado River basin. The formations are exposed at the surface in a circular shape surrounding the Llano Uplift. Recharge is received from precipitation and streams crossing the outcrop and migrates downward through fractures and solution channels to the saturated zone. The aquifer reaches a thickness of about 2,000 feet (610 m).

Ground water in the aquifer is commonly under artesian pressure. Natural discharge from the aquifer through springs supports the base flows of streams which include reaches of the Llano, San Saba, Pedernales, and Colorado Rivers. Wells yield as much as 1,000 gal/min (63 l/s). In most places, the water is comparatively low in dissolved solids, but hard. Usable quality water containing less than 3,000 mg/l extends downdip to depths of approximately 3,000 feet (914 m) below the land surface.

The annual effective recharge of the aquifer is estimated to be 29,400 acre-feet (36.3 hm^3), based on the approximate spring flow from the aquifer. This is 4,400 acre-feet (5.43 hm^3) or 18 percent more than was shown in the 1968 Plan. The current evaluation used the approximate aggregate spring flow based on actual gage measurements reported by Brune (1975). It is estimated that about 2 percent of the mean annual precipitation on the aquifer's outcrop would be necessary to support the estimated annual effective recharge to the aquifer.

Marble Falls Limestone

The Marble Falls Limestone aquifer is exposed along the northern and eastern flanks of the Llano Uplift, primarily in McCulloch, San Saba, and Lampasas Counties. The Marble Falls reaches a maximum thickness of 600 feet (183 m) and is a member of the Bend Group of Pennsylvanian age. Ground water occurs in cavities and fractures in the limestone. Wells producing from the aquifer may yield as much as 2,000 gal/min (130 l/s). There are also large springs issuing from the limestone.

The quality of water produced from the aquifer is usually suitable for most purposes in and near the outcrop area. The downdip limit of slightly saline water is unknown.

The quantity of ground water available as annual effective recharge is estimated to be 26,400 acre-feet (32.6 hm^3) based on spring flow data (Brune, 1975). The above annual effective recharge represents approximately 5 percent of the mean annual precipitation on the aquifer's outcrop. This aquifer was not included in the 1968 Texas Water Plan.

Blaine Gypsum

The Blaine Gypsum aquifer comprises zones of usable quality water in the Blaine Formation of Permian age which extends through Childress, Collingsworth, Cottle, Foard, Hardeman, King, and Wheeler Counties, and for the purposes of this evaluation, is confined to the Red River basin (Figure 12). This formation also crops out to the south in the Brazos and Colorado River basins; however, no major wells are known to be pumping from the aquifer in this area. Water quality is also poor in this southern area and the yields to existing wells are low. Within the area evaluated, ground water occurs principally in fractured and cavernous gypsum and associated dolomite beds. The maximum thickness of the aquifer is about 300 feet (91 m).

Yields of wells vary from a few gallons per minute to more than 1,500 gal/min (95 l/s) and average about 400 gal/min (25 l/s). The water generally contains between 2,000 and 5,000 mg/l dissolved solids of which calcium and sulfate are the principal constituents. Salinity of the water has increased as a result of sustained pumpage which causes saline water underlying the fresh water-bearing sections to be drawn into wells through the extensive fractures and solution channels. Almost all the water pumped from the aquifer is used for irrigation.

The estimated annual effective recharge of ground water from the Blaine Gypsum aquifer is 142,600 acre-feet (176 hm^3), an increase of 102,600 acre-feet (127 hm^3) or 257 percent over the 1968 estimate.

In the 1968 Texas Water Plan, the evaluation was based on a comparison of declines of water levels and pumpage (Peckham, 1967, p. 21). Maderak (1972, p. 12) stated that ground-water studies in Greer and Jackson Counties in Oklahoma (adjacent to Hardeman County, Texas) show that about 7 percent of the rainfall becomes effective recharge to this aquifer. In Hardeman County, Maderak (1972) judged that effective recharge to the Blaine is most likely between 5 and 7 percent of the mean annual precipitation. The current evaluation assumed a conservative 5 percent of the mean annual precipitation as effective recharge. This value was applied to the area of outcrop where usable quality water exists. The areal extent of this outcrop area was accurately delineated by using a geologic map and planimeter.

Igneous Rocks

In west Texas near Alpine and Marfa, igneous rocks occur that are of Tertiary age. Ground water is found in the fissures and fractures of lava flows, tuffs, and related igneous rocks which supply small to large amounts of good quality water for municipal, domestic, and other uses. Significant outcrops of Cretaceous and Precambrian igneous rocks also are found in far west Texas, Uvalde County, and the Llano Uplift area. However, data are insufficient to determine ground-water availability in these areas. The average annual quantity of ground water available as effective recharge from the igneous rocks near Alpine and Marfa is estimated to be about 10,700 acre-feet (13.2 hm^3). This estimate is based on 2.5 percent of the mean annual precipitation, which is considerably less than that previously used (Reed and Associates, 1972; Littleton and Audsley, 1957; Davis, 1961). During a recent hydrologic study of the Balmorhea area of the Trans-Pecos region, base-flow analyses revealed that the recharge in this area of Texas was much less than previously envisioned (Couch, 1979). Even so, the above estimate is 2,700 acre-feet (3.33 hm^3) or 34 percent more than the 1968 amount.

Marathon Limestone

The Marathon Limestone of Lower Ordovician age is present as an aquifer in north-central Brewster County of far west Texas. Here, the upfolded limestone is at or near the land surface and ground water occurs chiefly under water-table conditions in crevices, joints, and cavities. The aquifer ranges in thickness from 350 feet (107 m) to about 900 feet (274 m). The depth of most wells in this area is less than 250 feet (76 m). Well yields range from less than 10 gal/min (0.63 l/s) to more than 300 gal/min (19 l/s).

Water from the Marathon Limestone is generally of good quality except that it is very hard. The dissolved solids usually exceed 500 mg/l, but are less than 1,000 mg/l.

The estimated average annual ground water availability is 18,300 acre-feet (22.6 hm^3), a decrease of 11,700 acre-feet (14.4 hm^3) or 39 percent from the 1968 Texas Water Plan. This was estimated by using 2.5 percent of the mean annual precipitation. Earlier, the effective recharge was thought to be about 5 percent until recent studies made of incremental runoff and recharge in the Balmorhea area, resulted in the estimated lower percentage for effective recharge (Littleton and Audsley, 1957; Couch, 1979).

Bone Spring and Victorio Peak Limestones

The Bone Spring and Victorio Peak Limestones of Permian age underlie a narrow north-trending topographic basin in the northeastern corner of Hudspeth County between the Guadalupe Mountains on the east and the Diablo Plateau on the west. Ground water has collected in joints, fractures, and solution cavities in these limestone beds. The distribution of permeability is erratic, and yields of wells vary widely from about 150 gal/min (9.5 l/s) to more than 2,200 gal/min (140 l/s). The thickness of this aquifer may be as much as 2,000 feet (610 m).

Ground water withdrawn from this aquifer generally contains between 1,000 and 8,000 mg/l of dissolved solids. Although some of the water is suitable for irrigation, it is not desirable for municipal and domestic use.

The average annual amount of ground water available from the Bone Spring and Victorio Peak Limestones is 17,000 acre-feet (21.0 hm^3), which is the estimated annual effective recharge. Subsequent to the beginning of ground-water development in this area in 1947, water levels declined noticeably to the year 1968 with pumpage being as much as 100,000 acre-feet (123 hm^3) in 1960 (Peckham, 1963; and Davis and Gordon, 1970). However, an estimated pumpage from the aquifer of 18,000 acre-feet (22.2 hm^3) in 1949 caused a slight water-level decline of only 0.36 foot or 0.11 m (Scalapino, 1950). Based on this comparison of pumpage and water levels, it is reasonable to assume that a total yearly pumpage of 17,000 acre-feet (21.0 hm^3) will not cause a decline in water levels, and that this amount can be withdrawn perennially. This is 33,000 acre-feet (40.7 hm^3) or 66 percent less than that estimated in 1968.

Capitan Limestone

The Capitan Reef complex of Permian age follows the perimeter of the Delaware Basin in far west Texas and New Mexico. However, that portion of the reef discussed here concerning ground water available for development is primarily the Capitan Limestone where it underlies the Salt Bolson deposits in the Diablo Farms area along the Culberson and Hudspeth County line, and where the limestone crops out in the Apache Mountains of southeastern Culberson County.

In the Diablo Farms area, the reef has been penetrated by wells to depths greater than 1,000 feet (305 m). Water levels below the land surface may range from about 100 feet (30 m) to over 200 feet (61 m). Yields of wells commonly are more than 1,000 gal/min (63 l/s), and one well had an estimated yield of 6,000 gal/min (380 l/s). On the other hand, depths of wells in the Apache Mountains area range from 350 to 1,722 feet (107 to 525 m) and water levels vary from 280 to 1,000 feet (85 to 305 m) below the land surface (Couch, 1979). In this area, limited data indicate that yields of wells are as high as 400 gal/min (25 l/s).

The chemical quality of the ground water in the Diablo Farms vicinity ranges from 850 to 1,500 mg/l dissolved solids, and the principal constituents are calcium, sulfate, and bicarbonate. The iron content may be excessive for domestic and municipal use. In the Apache Mountains area, ground-water quality may be fresh in the central mountains and range to slightly saline elsewhere. The dissolved solids range from about 1,000 to 2,500 mg/l and the ratios of sulfate to chloride range from 1:1 to 1.5:1.

The estimated average annual ground water availability from the Capitan Limestone aquifer is 12,500 acre-feet (15.4 hm^3) as effective recharge and 375,000 acre-feet (462 hm^3) as water recoverable from storage (Appendix A). Of this amount, 2,500 acre-feet (3.08 hm^3) of effective recharge and the total 375,000 acre-feet (462 hm^3) recoverable from storage are available in the Diablo Farms area, and 10,000 acre-feet (12.3 hm^3) is available in the Apache Mountains area (Couch, 1979; and Gates and others, 1978).

Effective recharge was estimated to be between 2,000 and 3,000 acre-feet (2.47 to 3.70 hm^3) annually in the Diablo Farms area because the annual pumpage does not exceed 5,000 acre-feet (6.16 hm^3) and the water levels have shown a decline. The quantity recoverable from storage represents 75 percent of the total volume of water in storage considered to be of usable quality in the Diablo Farms area. The total storage volume was determined by multiplying the bulk volume of saturated material by a coefficient of storage of 0.05 (Gates and others, 1978).

The 10,000 acre-feet (12.3 hm) of annual effective recharge to the Capitan Limestone in the Apache Mountains was derived from a geohydrologic study in the Balmorhea district in Culberson, Jeff Davis, and Reeves Counties (Couch, 1979). The study concluded that 33,000 acre-feet (40.7 hm^3) flowed from the major springs in the area yet only about 23,900 acre-feet (29.5 hm^3) could be attributed as having originated in the Cretaceous aquifers. This conclusion was based on an incremental runoff and infiltration analysis of surface watersheds above the springs (Loyd Hamilton, 1974, oral communication). Consequently, the imbalance of 9,100 acre-feet (11.2 hm^3) must be coming from the Capitan and Rustler aquifers. In order to allow for a maximum portion of the flow at the springs to be attributed to the Cretaceous aquifers, Hamilton (1974, oral communication) assigned 4 percent of the mean annual precipitation to effective recharge in outcrop areas he could not evaluate due to a lack of surface gaging station control. In the current analysis, this percentage has been reduced slightly to 3.7 percent, thus increasing the imbalance of 9,100 acre-feet (11.2 hm^3) to 11,000 acre-feet (13.6 hm^3). Of this amount, about 10,000 acre-feet (12.3 hm^3) is from the Capitan Limestone and 1,000 acre-feet (1.23 hm^3) from the Rustler.

Supportive evidence is provided by comparison of the ground-water quality of the lower Cretaceous and Capitan Limestone aquifers. The ground water in wells penetrating the lower Cretaceous aquifer is of better quality than that discharged at the springs, which would indicate other sources supplying the springs. Also, the quality of water in the Capitan Limestone closely resembles that discharged from the large artesian springs of Toyahvale (Couch, 1979). The Capitan Limestone aquifer was not evaluated in the 1968 Plan.

Rustler

The Rustler aquifer of Permian age consists mainly of dolomite, limestone, and gypsum with a basal zone of sand, conglomerate, shale, and minor amounts of salt. The dolomite, limestone, and gypsum are vugular and cavernous. The aquifer reaches a maximum thickness of 500 feet (152 m). It crops out chiefly in eastern Culberson County and yields water to wells downdip as far east as Pecos County (Peckham, 1963).

Except where the porosity has developed in the dolomites and limestones, the coefficients of transmissibility and storage are believed to be low. Acidizing wells usually results in yields from 300 to 1,000 gal/min (19 to 63 l/s). One well in the Belding Farms area in Pecos County had a yield of 4,400 gal/min (280 l/s) when it was drilled. Water levels in wells range from less than 200 feet (61 m) below land surface up to a maximum of 1,800 feet (549 m) in heavily pumped areas.

Ground water from the Rustler aquifer is unsuitable for human consumption but can be used for irrigation, livestock, and oil reservoir water-flooding operations. The water generally contains from 2,000 to 6,000 mg/l dissolved solids with very high concentrations of calcium and sulfate.

The average annual ground-water availability from the aquifer is conservatively estimated to be 4,000 acre-feet (4.93 hm^3). Of this amount, 1,000 acre-feet (1.23 hm^3) is available in southeastern Culberson County near the northeastern flank of the Rounsaville Syncline where effective recharge in this area is thought to contribute to the spring flows in northeastern Jeff Davis County and southwestern Reeves County (Couch, 1979). The 3,000 acre-feet (3.70 hm^3) balance is probably a conservative estimate for the remainder of the aquifer lying primarily in Culberson, Reeves, and Pecos Counties where additional study is needed. However, water levels in the Belding Farms area of Pecos County have declined approximately 40 feet (12 m) since pumping began in the early 1960's, thus indicating that pumpage has exceeded the effective recharge for this vicinity. The availability estimate for the Rustler aquifer is 1,000 acre-feet (1.23 hm^3), or 20 percent, less than in the 1968 Texas Water Plan.

Nacatoch Sand

The Nacatoch Sand aquifer of Cretaceous age has a northeastward-trending outcrop 4 to 7 miles (6.4 to 11.3 km) wide which extends from northern Limestone County to Bowie County and the Red River (Figure 6). It is made up of light gray, unconsolidated to indurated, massive, glauconitic, calcareous sand, and marl ranging in thickness from 350 to 500 feet (107 to 152 m). The depth to the top of the aquifer is about 800 feet (244 m) along the southward extent of the fresh to slightly saline water line near the Bowie and Red River County line. In general, well yields can be as much as 500 gal/min (32 l/s). Flowing wells exist in Red River and Bowie Counties. The dissolved-solids content of the water generally ranges from 400 to 1,000 mg/l. The estimated average annual amount of ground water available as effective recharge from the Nacatoch Sand is 1,500 acre-feet (1.85 hm^3) which is based on a comparison of the pumpage and water-level trends. Pumpage has exceeded the effective recharge, and water levels have declined since development began in the aquifer in 1914 (Baker and others, 1963). This aquifer was included in the other undifferentiated aquifers in the 1968 Texas Water Plan.

Blossom Sand

The Blossom Sand aquifer of Cretaceous age crops out in central Fannin County and extends eastward through Lamar and Red River Counties. Lithologically, it consists of brownish to light grayish, unconsolidated, ferruginous, glauconitic, fine- to medium-grained sand interbedded with light to dark, sandy and chalky marl. Its thickness can range up to about 400 feet (122 m). In general, ground water from the aquifer is high in sodium and bicarbonate, fairly high in dissolved-solids content (500 to 2,000 mg/l), and is soft. Yields from wells may be as much as 650 gal/min (41 l/s) or more. The estimated average annual quantity of ground water available as effective recharge from the Blossom Sand is 700 acre-feet (0.86 hm^3) which is based on water-level trends and pumpage. Water levels have steadily declined since development began at Clarksville in 1905, which indicates that pumpage has exceeded the effective recharge (Baker and others, 1963). This aquifer was included with the other undifferentiated aquifers in the 1968 Texas Water Plan.

Purgatoire-Dakota

Underlying the Ogallala in the northwest corner of Dallam County in the Texas panhandle is the Purgatoire-Dakota aquifer of Cretaceous age. These beds are composed of white and yellow to brown sandstone, and gray shale. Its thickness ranges to more than 250 feet (76 m), and well yields are sufficient to support irrigation. A City of Texline well completed in the Purgatoire-Dakota has a dissolved-solids content of 283 mg/l. This aquifer has an annual effective recharge of 4,800 acre-feet (5.92 hm^3) based on an estimate by Brune (1970). The estimate used 0.25 inch (0.64 cm) recharge per year, one-half penetrating through the Ogallala area in Texas and one-half reaching Texas as ground-water underflow from New Mexico and Oklahoma. This amount of effective recharge is included with the Ogallala aquifer availability in Table 1 and Appendix A.

Other Undifferentiated

Some additional aquifers which, in local areas, are commonly the only source of ground water available are considered here. Approximately 2,400 acre-feet (2.96 hm^3) is estimated as annual effective recharge from water-bearing rocks of Permian (principally the Wichita Group) and Pennsylvanian (mainly the Cisco Group) ages. This is the same availability as shown for undifferentiated aquifers in the 1968 Texas Water Plan (Peckham, 1968). However, it excludes the Nacatoch and Blossom Sand which have been separated from this group since sufficient data are now available to make this possible. Aquifers remaining in this group provide small to moderate quantities of fresh to slightly saline water which are used mostly for domestic and livestock purposes. A small amount is being used by small municipalities. The aquifers are located in north-central Texas and are limited to zones 1 and 2 of the Red River basin; however, they are not shown on Figure 12.

Both the San Angelo Sandstone and the Whitehorse Group of Permian age locally provide very small amounts of water for public supply, irrigation, domestic, and livestock uses. Well yields range from small to moderate with the water quality ranging from fresh to moderately saline. These aquifers are in north-central Texas just east of the High Plains. Those of significance are found in zone 2 of the Red River basin. Available data are insufficient for quanitative estimates of availability for individual areas.

LIMITATIONS AND RECOMMENDATIONS

All ground-water availability values presented in this report are qualified as estimates and, as such, have limitations when compared to actual conditions. However, the methods used in estimating the quantities of ground water available were carefully selected according to each aquifer's geohydrologic characteristics and the availability of usable data. The economical feasibility of developing the available ground water was not evaluated.

Because of the complexity of the aquifers in Texas, it is recommended that the digital computer model method of analysis be applied to other aquifers as has been done with the Ogallala, Hueco Bolson, Carrizo-Wilcox, Edwards (Balcones Fault Zone), Trinity Group, and the Gulf Coast aquifers. In particular, the progressive nature of land-surface subsidence along the Gulf Coast and the continuous accumulation of knowledge warrants the use of the computer model as a method that is unequalled in keeping the ground-water availability estimates for the Gulf Coast aquifer in the most current and readily usable status possible. The development of good models and realistic aquifer evaluation criteria requires the combined efforts of geologists, hydrologists, engineers, economists, and computer programmers. Except for those aquifers in which continuous computer model evaluations are made, a review and updating of the ground-water availability of aquifers in the State should be carried out approximately every 5 years.

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Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer

Basin	Zone	Aquifer	Ground-water availability			Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet						Remaining recoverable storage, 2031 (acre-feet)
			Annual effective recharge (acre-feet)	1974 storage		1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	
				Recoverable (acre-feet)	Total (acre-feet)							
CANADIAN	1	Ogallala	34,200	69,769,000[1,2]	76,638,000	725,300	670,600	670,600	564,300	564,300	564,300	24,580,000
Do.		Zone Totals	34,200	69,769,000	76,638,000	725,300	670,600	670,600	564,300	564,300	564,300	24,580,000
Do.	2	Ogallala	56,400	88,617,600[1,2]	100,160,100[1]	1,031,000	913,300	913,300	714,600	714,600	714,600	37,182,700
Do.	2	Purgatoire-Dakota	(4,800)[3]	[4]	[4]	—	—	—	—	—	—	—
Do.		Zone Totals	56,400	88,617,600	100,160,100	1,031,000	913,300	913,300	714,600	714,600	714,600	37,182,700
		BASIN TOTALS	90,600	158,386,600	176,798,100	1,756,300	1,583,900	1,583,900	1,278,900	1,278,900	1,278,900	61,762,700
RED	1	Ogallala	64,400	48,526,600[1,2]	61,983,700[1]	1,108,700	825,100	825,100	422,400	422,400	343,600[5]	8,130,100
Do.	1	Alluvium (Seymour and other alluvial deposits)	6,100	198,700[1,2]	264,900[1]	9,700	9,700	9,700	9,700	9,700	6,100[5]	0
Do.	1	Blaine Gypsum	7,100[7]	[4]	[4]	7,100	7,100	7,100	7,100	7,100	7,100	—
Do.	1	Other (Permian and Pennsylvanian Undifferentiated-San Angelo and Whitehorse Group)	1,500	[4]	[4]	1,500	1,500	1,500	1,500	1,500	1,500	—
Do.		Zone Totals	79,100	48,725,300	62,248,600	1,127,000	843,400	843,400	440,700	440,700	358,300	8,130,100
Do.	2	Ogallala	600	79,200[1,2]	139,800[1]	3,000	2,200	2,200	1,000	1,000	600[5]	0
Do.	2	Alluvium (Seymour and other alluvial deposits)	113,700	2,040,300[6]	2,720,400[1]	150,100	150,100	150,100	150,100	150,100	113,700	—
Do.	2	Blaine Gypsum	135,500[7]	[4]	[4]	135,500	135,500	135,500	135,500	135,500	135,500	—
Do.	2	Trinity Group	200	2,900[8]	[4]	200	200	200	200	200	200	0[9]
Do.	2	Other (Permian and Pennsylvanian Undifferentiated)	900	[4]	[4]	900	900	900	900	900	900	—
Do.		Zone Totals	250,900	2,122,400	2,860,200	289,700	288,900	288,900	287,700	287,700	250,900	0
Do.	3	Trinity Group	3,500	54,300[8]	[4]	4,600	4,600	4,600	4,600	4,600	3,500	0[9]
Do.	3	Woodbine	14,000	[4]	[4]	14,000	14,000	14,000	14,000	14,000	14,000	—
Do.	3	Others (Nacatoch-200 and Blossom-300)	500	[4]	[4]	500	500	500	500	500	500	—
Do.		Zone Totals	18,000	54,300	—	19,100	19,100	19,100	19,100	19,100	18,000	0
Do.		BASIN TOTALS	348,000	50,902,000	65,108,800	1,435,800	1,151,400	1,151,400	747,500	747,500	627,200	8,130,100

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

Basin	Zone	Aquifer	Ground-water availability			Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet						Remaining recoverable storage, 2031 (acre-feet)
			Annual effective recharge (acre-feet)	1974 storage								
				Recoverable (acre-feet)	Total (acre-feet)	1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	
SULPHUR	1	Trinity Group	0[10]	68,400[11]	[4]	1,300	1,300	1,300	1,300	1,300	0[10]	0[9]
Do.	1	Carrizo-Wilcox	4,000	3,000[11]	[4]	4,100	4,100	4,100	4,100	4,100	4,000	0[9]
Do.	1	Woodbine	[4]	[4]	[4]	—	—	—	—	—	—	—
Do.	1	Queen City	7,000[12]	[4]	[4]	7,000	7,000	7,000	7,000	7,000	7,000	—
Do.	1	Others (Nacatoch-1,300 and Blossom-400)	1,700	[4]	[4]	1,700	1,700	1,700	1,700	1,700	1,700	—
Do.		Zone Totals	12,700	71,400	—	14,100	14,100	14,100	14,100	14,100	12,700	0
Do.		BASIN TOTALS	12,700	71,400	—	14,100	14,100	14,100	14,100	14,100	12,700	0
CYPRESS	1	Carrizo-Wilcox	15,000	42,400[11]	[4]	15,800	15,800	15,800	15,800	15,800	15,000	0[9]
Do.	1	Queen City	234,500[12]	[4]	[4]	234,500	234,500	234,500	234,500	234,500	234,500	—
Do.		Zone Totals	249,500	42,400	—	250,300	250,300	250,300	250,300	250,300	249,500	0
Do.		BASIN TOTALS	249,500	42,400	—	250,300	250,300	250,300	250,300	250,300	249,500	0
SABINE	1	Trinity Group	0[10]	23,200[11]	[4]	400	400	400	400	400	0[10]	0[9]
Do.	1	Carrizo-Wilcox	40,000	68,800[11]	[4]	41,300	41,300	41,300	41,300	41,300	40,000	0[9]
Do.	1	Queen City	137,800[12]	[4]	[4]	137,800	137,800	137,800	137,800	137,800	137,800	—
Do.		Zone Totals	177,800	92,000	—	179,500	179,500	179,500	179,500	179,500	177,800	0
Do.	2	Carrizo-Wilcox	4,000	6,700[11]	[4]	4,100	4,100	4,100	4,100	4,100	4,100	0[9]
Do.	2	Sparta	7,400[13]	[4]	[4]	7,400	7,400	7,400	7,400	7,400	7,400	—
Do.	2	Gulf Coast	54,000	[4]	[4]	54,000	54,000	54,000	54,000	54,000	54,000	—
Do.		Zone Totals	65,400	6,700	—	65,500	65,500	65,500	65,500	65,500	65,400	0
Do.		BASIN TOTALS	243,200	98,700	—	245,000	245,000	245,000	245,000	245,000	243,200	0
NECHES	1	Carrizo-Wilcox	124,600	198,400[8]	[4]	128,400	128,400	128,400	128,400	128,400	124,600	0[9]
Do.	1	Queen City	253,200[12]	[4]	[4]	253,200	253,200	253,200	253,200	253,200	253,200	—
Do.	1	Sparta	30,700[13]	[4]	[4]	30,700	30,700	30,700	30,700	30,700	30,700	—
Do.		Zone Totals	408,500	198,400	—	412,300	412,300	412,300	412,300	412,300	408,500	0
Do.	2	Carrizo-Wilcox	25,400	39,300	[4]	26,100	26,100	26,100	26,100	26,100	25,400	0[9]

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

			Ground-water availability			Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet						Remaining recoverable storage, 2031 (acre-feet)
			Annual effective recharge (acre-feet)	1974 storage								
Basin	Zone	Aquifer		Recoverable (acre-feet)	Total (acre-feet)	1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	
NECHES	2	Queen City	8,100	[4]	[4]	8,100	8,100	8,100	8,100	8,100	8,100	—
Do.	2	Sparta	23,700[13]	[4]	[4]	23,700	23,700	23,700	23,700	23,700	23,700	—
Do.	2	Gulf Coast	101,000	[4]	[4]	101,000	101,000	101,000	101,000	101,000	101,000	—
Do.		Zone Totals	158,200	39,300	—	158,900	158,900	158,900	158,900	158,900	158,200	0
Do.		BASIN TOTALS	566,700	237,700	—	571,200	571,200	571,200	571,200	571,200	566,200	0
TRINITY	1	Trinity Group	45,400	465,800	[4]	54,200	54,200	54,200	54,200	54,200	45,400	0[9]
Do.	1	Woodbine	11,100	[4]	[4]	11,100	11,100	11,100	11,100	11,100	11,100	—
Do.	1	Carrizo-Wilcox	13,400	36,100	[4]	14,100	14,100	14,100	14,100	14,100	13,400	0[9]
Do.	1	Queen City	500	[4]	[4]	500	500	500	500	500	500	—
Do.		Zone Totals	70,400	501,900	—	79,900	79,900	79,900	79,900	79,900	70,400	—
Do.	2	Trinity Group	100	400	[4]	100	100	100	100	100	100	0[9]
Do.	2	Woodbine	0	[4]	[4]	0	0	0	0	0	0	—
Do.	2	Carrizo-Wilcox	65,300	175,500	[4]	68,600	68,600	68,600	68,600	68,600	65,300	0[9]
Do.	2	Queen City	14,500	[4]	[4]	14,500	14,500	14,500	14,500	14,500	14,500	—
Do.	2	Sparta	34,800	[4]	[4]	34,800	34,800	34,800	34,800	34,800	34,800	—
Do.	2	Gulf Coast	6,100	[4]	[4]	6,100	6,100	6,100	6,100	6,100	6,100	—
Do.		Zone Totals	120,800	175,900	—	124,100	124,100	124,100	124,100	124,100	120,800	—
Do.	3	Carrizo-Wilcox	300	600	[4]	300	300	300	300	300	300	0[9]
Do.	3	Sparta	200	[4]	[4]	200	200	200	200	200	200	—
Do.	3	Gulf Coast	55,300	[4]	[4]	55,300	55,300	55,300	55,300	55,300	55,300	—
Do.		Zone Totals	55,800	600	—	55,800	55,800	55,800	55,800	55,800	55,800	—
Do.		BASIN TOTALS	247,000	678,400	—	259,800	259,800	259,800	259,800	259,800	247,000	0
SAN JACINTO	1	Gulf Coast	337,000	[4]	[4]	337,000	337,000	337,000	337,000	337,000	337,000	—
Do.		Zone Totals	337,000	—	—	337,000	337,000	337,000	337,000	337,000	337,000	—
Do.		BASIN TOTALS	337,000	—	—	337,000	337,000	337,000	337,000	337,000	337,000	—

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

			Ground-water availability			Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet						
				1974 storage								
Basin	Zone	Aquifer	Annual effective recharge (acre-feet)	Recoverable (acre-feet)	Total (acre-feet)	1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	Remaining recoverable storage, 2031 (acre-feet)
BRAZOS	1	Ogallala	71,300	55,444,600[1,2]	71,291,600[1]	1,294,800	986,400	986,400	616,200	616,200	616,200	4,791,000
Do.	1	Edwards-Trinity (High Plains)	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]
Do.	1	Alluvium (Seymour and other alluvial deposits)	500	0	0	500	500	500	500	500	500	0
Do.	1	Santa Rosa	100	[4]	[4]	100	100	100	100	100	100	—
Do.		Zone Totals	71,900	55,444,600	71,291,600	1,295,400	987,000	987,000	616,800	616,800	616,800	4,791,000
Do.	2	Ogallala	300	52,800	93,200	1,900	1,400	1,400	600	600	300	0
Do.	2	Edwards-Trinity (High Plains)	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]
Do.	2	Alluvium (Seymour and other alluvial deposits)	86,900	1,182,100	1,576,100	108,000	108,000	108,000	108,000	108,000	86,900	0[14]
Do.	2	Santa Rosa	3,300	[4]	[4]	3,300	3,300	3,300	3,300	3,300	3,300	—
Do.	2	Trinity Group	8,000	0	0	8,000	8,000	8,000	8,000	8,000	8,000	—
Do.		Zone Totals	98,500	1,234,900	1,669,300	121,200	120,700	120,700	119,900	119,900	98,500	0
Do.	3	Trinity Group	10,800	146,700[8]	[4]	13,600	13,600	13,600	13,600	13,600	10,800	0[9]
Do.	3	Brazos River Alluvium	18,100	250,700	334,300	22,600	22,600	22,600	22,600	22,600	18,100	0
Do.	3	Woodbine	1,000	[4]	[4]	1,000	1,000	1,000	1,000	1,000	1,000	—
Do.		Zone Totals	29,900	397,400	334,300	37,200	37,200	37,200	37,200	37,200	29,900	0
Do.	4	Trinity Group	13,600	183,700[8]	[4]	17,000	17,000	17,000	17,000	17,000	13,600	0[9]
Do.	4	Edwards (Balcones Fault Zone)	5,000	[4]	[4]	5,000	5,000	5,000	5,000	5,000	5,000	—
Do.	4	Carrizo-Wilcox	11,100	16,100[8]	[4]	11,400	11,400	11,400	11,400	11,400	11,100	0[9]
Do.	4	Queen City	—	—	[4]	—	—	—	—	—	—	—
Do.	4	Marble Falls	6,300	[4]	[4]	6,300	6,300	6,300	6,300	6,300	6,300	—
Do.	4	Brazos River Alluvium	—	—	[4]	—	—	—	—	—	—	—
Do.		Zone Totals	36,000	199,800	—	39,700	39,700	39,700	39,700	39,700	36,000	0
Do.	5	Trinity Group	200	9,900[8]	[4]	400	400	400	400	400	200	0[9]
Do.	5	Brazos River Alluvium	48,600	673,300	897,700	60,600	60,600	60,600	60,600	60,600	48,600	0

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

Basin	Zone	Aquifer	Ground-water availability: Annual effective recharge (acre-feet)	Ground-water availability: 1974 storage: Recoverable (acre-feet)	Ground-water availability: 1974 storage: Total (acre-feet)	Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet: 1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	Remaining recoverable storage, 2031 (acre-feet)
BRAZOS	5	Carrizo-Wilcox	118,200	168,300[8]	[4]	121,400	121,400	121,400	121,400	121,400	118,200	0[9]
Do.	5	Queen City	2,700	[4]	[4]	2,700	2,700	2,700	2,700	2,700	2,700	—
Do.	5	Sparta	7,000	[4]	[4]	7,000	7,000	7,000	7,000	7,000	7,000	—
Do.	5	Gulf Coast	21,100	[4]	[4]	21,100	21,100	21,100	21,100	21,100	21,100	—
Do.		Zone Totals	197,800	851,500	897,700	213,200	213,200	213,200	213,200	213,200	197,800	0
Do.	6	Brazos River Alluvium	33,300	461,300	615,100	41,500	41,500	41,500	41,500	41,500	33,300	0
Do.	6	Gulf Coast	51,400	[4]	[4]	51,400	51,400	51,400	51,400	51,400	51,400	—
Do.		Zone Totals	84,700	461,300	615,100	92,900	92,900	92,900	92,900	92,900	84,700	0
Do.		BASIN TOTALS	518,800	58,589,500	74,808,000	1,799,600	1,490,700	1,119,700	1,119,700	1,119,700	1,063,700	4,791,000
COLORADO	1	Ogallala	70,100	19,184,200	29,565,700	519,400	413,000	413,000	252,200	252,200	184,300	1,465,800
Do.	1	Edwards-Trinity (High Plains)	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]	[3]
Do.	1	Edwards-Trinity (Plateau)	31,500	(6,246,400)[1,6,15]	(8,328,500)[1,15]	31,500	31,500	31,500	31,500	31,500	31,500	—
Do.		Zone Totals	101,600	19,184,200	29,565,700	550,900	444,500	444,500	283,700	283,700	215,800	1,465,800
Do.	2	Ogallala	900	80,000	210,000	3,900	2,800	2,800	900	900	900	0
Do.	2	Edwards-Trinity (Plateau)	147,300	(28,044,100)[1,6,15]	(37,391,900)[1,15]	147,300	147,300	147,300	147,300	147,300	147,300	—
Do.	2	Ellenburger-San Saba	17,200	[4]	[4]	17,200	17,200	17,200	17,200	17,200	17,200	—
Do.	2	Hickory	8,700	[4]	[4]	8,700	8,700	8,700	8,700	8,700	8,700	—
Do.	2	Leona (Alluvium)	8,000	130,300	[4]	10,500	10,500	10,500	10,500	10,500	8,000	—
Do.	2	Marble Falls	18,900	[4]	[4]	18,900	18,900	18,900	18,900	18,900	18,900	—
Do.	2	Santa Rosa	20,100	[4]	[4]	20,100	20,100	20,100	20,100	20,100	20,100	—
Do.	2	Trinity Group	10,000	32,100[8]	[4]	10,600	10,600	10,600	10,600	10,600	10,000	—
Do.		Zone Totals	231,100	242,400	210,000	237,200	236,100	236,100	234,200	234,200	231,100	0
Do.	3	Edwards-Trinity (Plateau)	83,300	(4,368,500)[1,6,15]	(5,824,700)[1,15]	83,300	83,300	83,300	83,300	83,300	83,300	—
Do.	3	Ellenburger-San Saba	12,200	[4]	[4]	12,200	12,200	12,200	12,200	12,200	12,200	—

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

Basin	Zone	Aquifer	Ground-water availability: Annual effective recharge (acre-feet)	Ground-water availability: 1974 storage: Recoverable (acre-feet)	Ground-water availability: 1974 storage: Total (acre-feet)	Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet: 1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	Remaining recoverable storage, 2031 (acre-feet)
COLORADO	3	Hickory	43,900	[4]	[4]	43,900	43,900	43,900	43,900	43,900	43,900	—
Do.	3	Edwards (Balcones Fault Zone)	8,700	[4]	[4]	8,700	8,700	8,700	8,700	8,700	8,700	—
Do.	3	Marble Falls	1,200	[4]	[4]	1,200	1,200	1,200	1,200	1,200	1,200	—
Do.	3	Trinity Group	3,300	20,500[8]	[4]	3,700	3,700	3,700	3,700	3,700	3,300	0[9]
Do.	3	Carrizo-Wilcox	49,200	46,900[8]	[4]	50,100	50,100	50,100	50,100	50,100	50,100	0[9]
Do.	3	Queen City	3,700	[4]	[4]	3,700	3,700	3,700	3,700	3,700	3,700	
Do.	3	Sparta	10,000	[4]	[4]	10,000	10,000	10,000	10,000	10,000	10,000	—
Do.	3	Gulf Coast	26,000	[4]	[4]	26,000	26,000	26,000	26,000	26,000	26,000	—
Do.		Zone Totals	241,500	67,400	—	242,800	242,800	242,800	242,800	242,800	242,800	0
Do.		BASIN TOTALS	574,200	19,494,000	29,775,700	1,030,900	923,400	923,400	760,700	760,700	688,400	1,465,800
LAVACA	1	Gulf Coast	86,000	[4]	[4]	86,000	86,000	86,000	86,000	86,000	86,000	—
Do.		Zone Total	86,000	—	—	86,000	86,000	86,000	86,000	86,000	86,000	—
Do.		BASIN TOTALS	86,000		—	86,000	86,000	86,000	86,000	86,000	86,000	
GUADALUPE	1	Edwards-Trinity (Plateau)	(8,100)[16]	(569,000)[4,6,16]	(759,000)	—			—	—	—	
Do.	1	Trinity Group	(20,000)[16]	[4]	[4]	—	—	—			—	—
Do.	1	Edwards (Balcones Fault Zone)	38,200[17]	[4,15]	[4,15]	38,200	38,200	38,200	38,200	38,200	38,200	
Do.		Zone Totals	38,200	—	—	38,200	38,200	38,200	38,200	38,200	38,200	—
Do.	2	Carrizo-Wilcox	38,600	476,400[17]	[4]	46,500	46,500	46,500	46,500	46,500	38,600	0[9]
Do.	2	Queen City	8,000	[4]	[4]	8,000	8,000	8,000	8,000	8,000	8,000	
Do.	2	Sparta	20,000	[4]	[4]	20,000	20,000	20,000	20,000	20,000	20,000	—
Do.	2	Gulf Coast	21,000	[4]	[4]	21,000	21,000	21,000	21,000	21,000	21,000	
Do.		Zone Totals	87,600	476,400	—	95,500	95,500	95,500	95,500	95,500	87,600	0
Do.		BASIN TOTALS	125,800	476,400		133,700	133,700	133,700	133,700	133,700	125,800	0
SAN ANTONIO	1	Edwards-Trinity (Plateau)	(24,900)[16]	[4]	[4]	—			—	—	—	—

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

Basin	Zone	Aquifer	Ground-water availability: Annual effective recharge (acre-feet)	1974 storage: Recoverable (acre-feet)	1974 storage: Total (acre-feet)	Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet: 1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	Remaining recoverable storage, 2031 (acre-feet)
SAN ANTONIO	1	Trinity Group	(1,100)[16]	[4]	[4]	–	–	–	–	–	–	–
Do.	1	Edwards (Balcones Fault Zone)	285,100	[4,15]	[4,15]	285,100	285,100	285,100	285,100	285,100	285,100	–
Do.	1	Carrizo-Wilcox	10,200	243,300[18]	[4]	14,300	14,300	14,300	14,300	14,300	10,200	0[9]
Do.		Zone Totals	295,300	243,300	–	299,400	299,400	299,400	299,400	299,400	295,300	–
Do.	2	Carrizo-Wilcox	33,200	792,200[18]	[4]	46,400	46,400	46,400	46,400	46,400	33,200	0[9]
Do.	2	Queen City	3,600	[4]	[4]	3,600	3,600	3,600	3,600	3,600	3,600	–
Do.	2	Sparta	10,000	[4]	[4]	10,000	10,000	10,000	10,000	10,000	10,000	–
Do.	2	Gulf Coast	13,000	[4]	[4]	13,000	13,000	13,000	13,000	13,000	13,000	–
Do.		Zone Totals	59,800	792,200	–	73,000	73,000	73,000	73,000	73,000	59,800	0
Do.		BASIN TOTALS	355,100	1,035,500	–	372,400	372,400	372,400	372,400	372,400	355,100	0
NUECES	1	Edwards-Trinity (Plateau)	(107,500)[16]	[4]	[4]	–	–	–	–	–	–	–
Do.	1	Trinity Group	[4,16]	[4]	[4]	–	–	–	–	–	–	–
Do.	1	Edwards (Balcones Fault Zone)	101,700	[4,15]	[4,15]	101,700	101,700	101,700	101,700	101,700	101,700	–
Do.	1	Carrizo-Wilcox	78,700	9,573,500[18]	[4]	238,300	238,300	238,300	238,300	238,300	78,700	0
Do.	1	Queen City	8,500	[4]	[4]	8,500	8,500	8,500	8,500	8,500	8,500	–
Do.	1	Sparta	20,000	[4]	[4]	20,000	20,000	20,000	20,000	20,000	20,000	–
Do.	1	Gulf Coast	14,000	[4]	[4]	14,000	14,000	14,000	14,000	14,000	14,000	–
Do.		Zone Totals	222,900	9,573,500	–	382,500	382,500	382,500	382,500	382,500	222,900	0
Do.		BASIN TOTALS	222,900	9,573,500	–	382,500	382,500	382,500	382,500	382,500	222,900	0
RIO GRANDE	1	Mesilla Bolson	18,000	560,000[19]	560,000[19]	32,900	41,400	41,400	41,400	39,500	37,800	140,000[20]
Do.	1	Hueco Bolson	6,000	10,600,000[21]	10,600,000[21]	90,600	124,700	167,300	234,800	304,300	373,500	2,730,000[20]
Do.	1	Salt Bolson	0[22]	[22]	[4]	–	–	–	–	–	–	–
Do.	1	Red Light Draw Bolson	2,000	450,000[23]	600,000	10,300	10,300	10,300	10,300	10,300	2,000	0[24]
Do.	1	Green River Valley Bolson	300	52,500[23]	70,000	1,200	1,200	1,200	1,200	1,200	300	0[25]

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

			Ground-water availability			Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet						Remaining recoverable storage, 2031 (acre-feet)
			Annual effective recharge (acre-feet)	1974 storage								
Basin	Zone	Aquifer		Recoverable (acre-feet)	Total (acre-feet)	1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	
RIO GRANDE	1	Capitan Limestone	1,200	187,500[23]	250,000	4,700	4,700	4,700	4,700	4,700	1,200	0[26]
Do.	1	Bone Spring and Victorio Peak Limestones	17,000	[4]	[4]	17,000	17,000	17,000	17,000	17,000	17,000	—
Do.		Zone Totals	44,500	11,850,000	12,080,000	156,700	199,300	241,900	309,400	377,000	431,800	2,870,000
Do.	2	Salt Bolson	14,000	5,677,500[23]	7,570,000	119,100	119,100	119,100	119,100	119,100	14,000	0[27]
Do.	2	Green River Valley Bolson	700	157,500[23]	210,000	3,700	3,700	3,700	3,700	3,700	700	0[28]
Do.	2	Presidio and Redford Bolsons	7,000	750,000[23]	1,000,000	20,900	20,900	20,900	20,900	20,900	7,900	0[29]
Do.	2	Edwards-Trinity (Plateau)	339,200	(50,038,300)[6,15]	(66,717,700)[15]	339,200	339,200	339,200	339,200	339,200	339,200	—
Do.	2	Igneous Rocks	10,700	[4]	[4]	10,700	10,700	10,700	10,700	10,700	10,700	—
Do.	2	Marathon Limestone	18,300	[4]	[4]	18,300	18,300	18,300	18,300	18,300	18,300	—
Do.	2	Capitan Limestone	11,300	187,500[6,23]	250,000	14,700	14,700	14,700	14,700	14,700	11,300	0[30]
Do.	2	Rustler[31]	1,000	[4]	[4]	1,000	1,000	1,000	1,000	1,000	1,000	—
Do.	2	Carrizo-Wilcox	13,700	160,300[32]	[4]	16,400	16,400	16,400	16,400	16,400	13,700	0[9]
Do.	2	Gulf Coast	11,400	[4]	[4]	11,400	11,400	11,400	11,400	11,400	11,400	—
Do.		Zone Totals	427,300	6,932,800	9,030,000	555,400	565,400	555,400	555,400	555,400	427,300	0
Do.	3	Edwards-Trinity (Plateau)	174,700	(56,170,900)[6,15]	(74,894,600)[15]	174,700	174,700	174,700	174,700	174,700	174,700	—
Do.	3	Cenozoic Alluvium	70,800	9,481,300[33]	30,000,000	249,700	249,700	249,700	249,700	249,700	70,800	0[34]
Do.	3	Rustler[31]	3,000	[4]	[4]	3,000	3,000	3,000	3,000	3,000	3,000	—
Do.	3	Santa Rosa	[35]	[35]	[35]	—	—	—	—	—	—	—
Do.		Zone Totals	248,500	9,481,300	—	427,400	427,400	427,400	424,400	427,400	248,500	0
Do.		BASIN TOTALS	720,300	28,264,100	51,110,000	1,139,500	1,182,100	1,224,700	1,292,200	1,359,800	1,107,600	2,870,000
NECHES-TRINITY	1	Gulf Coast	2,600	[4]	[4]	2,600	2,600	2,600	2,600	2,600	2,600	—
Do.		Zone Totals	2,600	—	—	2,600	2,600	2,600	2,600	2,600	2,600	—

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer

Basin	Zone	Aquifer	Ground-water availability			Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet						Remaining recoverable storage, 2031 (acre-feet)
			Annual effective recharge (acre-feet)	1974 storage Recoverable (acre-feet)	1974 storage Total (acre-feet)	1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	
NECHES-TRINITY	2	Gulf Coast	8,400	[4]	[4]	8,400	8,400	8,400	8,400	8,400	8,400	—
Do.		Zone Totals	8,400	—	—	8,400	8,400	8,400	8,400	8,400	8,400	—
Do.		BASIN TOTALS	11,000	—	—	11,000	11,000	11,000	11,000	11,000	11,000	—
TRINITY-SAN JACINTO	1	Gulf Coast	42,000	[4]	[4]	42,000	42,000	42,000	42,000	42,000	42,000	—
Do.		Zone Totals	42,000	—	—	42,000	42,000	42,000	42,000	42,000	42,000	—
Do.		BASIN TOTALS	42,000	—	—	42,000	42,000	42,000	42,000	42,000	42,000	—
SAN JACINTO-BRAZOS	1	Gulf Coast	110,500	[4]	[4]	110,500	110,500	110,500	110,500	110,500	110,500	—
Do.		Zone Totals	110,500	—	—	110,500	110,500	110,500	110,500	110,500	110,500	—
Do.		BASIN TOTALS	110,500	—	—	110,500	110,500	110,500	110,500	110,500	110,500	—
BRAZOS-COLORADO	1	Gulf Coast	68,000	[4]	[4]	68,000	68,000	68,000	68,000	68,000	68,000	—
Do.		Zone Totals	68,000	—	—	68,000	68,000	68,000	68,000	68,000	68,000	—
Do.		BASIN TOTALS	68,000	—	—	68,000	68,000	68,000	68,000	68,000	68,000	—
COLORADO-LAVACA	1	Gulf Coast	8,000	[4]	[4]	8,000	8,000	8,000	8,000	8,000	8,000	—
Do.		Zone Totals	8,000	—	—	8,000	8,000	8,000	8,000	8,000	8,000	—
Do.		BASIN TOTALS	8,000	—	—	8,000	8,000	8,000	8,000	8,000	8,000	—
LAVACA-GUADALUPE	1	Gulf Coast	48,000	[4]	[4]	48,000	48,000	48,000	48,000	48,000	48,000	—
Do.		Zone Totals	48,000	—	—	48,000	48,000	48,000	48,000	48,000	48,000	—
Do.		BASIN TOTALS	48,000	—	—	48,000	48,000	48,000	48,000	48,000	48,000	—
SAN ANTONIO-NUECES	1	Gulf Coast	30,000	[4]	[4]	30,000	30,000	30,000	30,000	30,000	30,000	—
Do.		Zone Totals	30,000	—	—	30,000	30,000	30,000	30,000	30,000	30,000	—
Do.		BASIN TOTALS	30,000	—	—	30,000	30,000	30,000	30,000	30,000	30,000	—

See footnotes at end of table.

Appendix A.—Estimates of Ground-Water Availability in Texas by River Basin, Coastal Basin, Zone, and Aquifer—Continued

Basin	Zone	Aquifer	Ground-water availability: Annual effective recharge (acre-feet)	Ground-water availability: 1974 storage: Recoverable (acre-feet)	Ground-water availability: 1974 storage: Total (acre-feet)	Projected average annual ground-water availability (storage depletion and effective recharge), in acre-feet: 1980-1989	1990-1999	2000-2009	2010-2019	2020-2029	2030	Remaining recoverable storage, 2031 (acre-feet)
NUECES-RIO GRANDE	1	Gulf Coast[36]	55,800	[4]	[4]	55,800	55,800	55,800	55,800	55,800	55,800	—
Do.		Zone Totals	55,800	—	—	55,800	55,800	55,800	55,800	55,800	55,800	—
Do.	2	Gulf Coast[36]	59,200	[4]	[4]	59,200	59,200	59,200	59,200	59,200	59,200	—
Do.		Zone Totals	59,200	—	—	59,200	59,200	59,200	59,200	59,200	59,200	—
Do.		BASIN TOTALS	115,000	—	—	115,000	115,000	115,000	115,000	115,000	115,000	—
		GRAND TOTAL ALL BASINS	5,130,300	327,850,200	397,600,600	10,246,600	9,416,000	9,458,600	8,283,500	8,351,100	7,644,200	79,019,600

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[1] Unconfined storage.
[2] Recoverable storage based on 20 feet of saturated thickness remaining.
[3] Included with Ogallala and excluded from totals.
[4] Not determined.
[5] Recoverable storage depleted at the end of previous year in some counties.
[6] Recoverable storage based on 0.75 times the total storage.
[7] Suitable for irrigation and livestock use only.
[8] Confined storage.
[9] An undetermined amount will be in artesian storage in January 2031.
[10] All of the average annual availability is from artesian storage.
[11] Recoverable artesian storage in 1976.
[12] Ground water is corrosive (low pH), and has high iron concentrations, generally exceeding 0.3 milligrams per liter.
[13] Ground water has very high iron concentrations, locally exceeding several milligrams per liter.
[14] About 394,100 acre-feet will be in total storage in January 2031.
[15] Pumpage from aquifer directly depletes surface supplies. Data in parentheses ( ) are not included in zone or basin totals.
[16] Not included because extensive development of the natural recharge or storage of the aquifer in the zone or basin would cause a decrease in the base flow of streams and underflow to the Edwards (Balcones Fault Zone) aquifer, thus affecting the natural recharge to the Edwards (Balcones Fault Zone) aquifer. Data in parentheses ( ) are not included in zone or basin totals.
[17] Recoverable artesian storage available from 1970 to 2030.
[18] Recoverable storage for 1970.
[19] Recoverable water-table and artesian storage in 1973 and is 100 percent of the freshwater in storage.
[20] These are the theoretical amounts of fresh ground water remaining in recoverable storage at the end of the year 2030.
[21] Recoverable water-table and artesian storage in 1973 and is 100 percent of freshwater in storage.
[22] Negligible effective recharge and ground water recoverable from storage.
[23] Recoverable water-table storage in 1976.
[24] Approximately 150,000 acre-feet will be in water-table storage in January 2031.
[25] Approximately 17,500 acre-feet will be in water-table storage in January 2031.
[26] Approximately 125,000 acre-feet will be in water-table storage in January 2031.
[27] Approximately 1,892,000 acre-feet will be in water-table storage in January 2031.
[28] Approximately 52,500 acre-feet will be in water-table storage in January 2031.
[29] Approximately 250,000 acre-feet will be in water-table storage in January 2031.
[30] Approximately 125,000 acre-feet will be in water-table storage in January 2031.
[31] Ground water is not suitable for human consumption but is used for irrigation, livestock watering, and oil field water-flooding operations.
[32] Recoverable artesian storage in 1970.
[33] The amount of fresh to slightly saline ground water in recoverable water-table storage in 1976.
[34] Approximately 21,000,000 acre-feet of fresh to slightly saline ground water will be in water-table storage in January 2031.
[35] Availability for Santa Rosa aquifer included with Cenozoic Alluvium aquifer in Ward and Winkler Counties.
[36] Includes Rio Grande Alluvium aquifer.
[37] An additional 34,000 acre-feet would be available as annual effective recharge had not constraints been used to provide minimum spring flow at San Marcos Springs to maintain the environment of that area.

Appendix B.—Hydrologic Units and Their Water-Bearing Properties

	Water-bearing properties	Geologic units	Aquifer thickness (feet)	Lithologic properties
MAJOR AQUIFER				
Ogallala	Yields moderate to large amounts of water in the High Plains. The water is generally fresh to slightly saline except where local contamination has occurred. The greatest saturated thickness occurs in the North Plains area and ranges up to 525 feet with thicknesses as much as 200 feet in the area south of Lubbock.	Ogallala Formation of Pliocene age	0-900	Unconsolidated, varicolored sand, silt, clay, and gravel with some caliche beds.
Carrizo-Wilcox	The Wilcox portion of the aquifer is poorly developed southwest of the Guadalupe River; to the northeast the Carrizo and Wilcox are about equal in importance. Usually yields moderate to large amounts of fresh to slightly saline water.	Carrizo Formation and Wilcox Group of Eocene age	150-3,000	Ferruginous, cross-bedded sand with clay, sand, silt, and gravel.
Edwards (Balcones Fault Zone)	Yields moderate to large amounts of fresh to slightly saline water. Acidizing usually improves yields of wells. Water quality deteriorates rapidly toward the southeast. The four largest springs in Texas (Comal, San Marcos, San Felipe, and Barton) issue from this aquifer.	Georgetown, Edwards, and Comanche Peak Formations of Cretaceous age	350-600	Massive to thin-bedded, nodular, cherty, gypsiferous, argillaceous limestone, dolomite, and shale. Some beds are highly cavernous.
Trinity Group	Yields small to large amounts of fresh to slightly saline water. Much of the aquifer has been overdeveloped, especially in the Fort Worth-Dallas area.	Trinity Group of Cretaceous age	100-1,200	Sand with silt, shale, and clay. Gravel and conglomerate usually found at the base. Limestone and dolomite replaces sand toward the southeast.
Alluvium and Bolson Deposits	Bolsons are the principal aquifers in the upper Rio Grande basin, supplying small to large quantities of fresh to moderately saline water. Elsewhere alluvium yields may be small to large, and water quality ranges from fresh to slightly saline.	Cenozoic and Recent Formations of Tertiary and Holocene age	0-9,000	Unconsolidated and partially consolidated sand, silt, gravel, clay, and boulders with caliche, gypsum, conglomerate, and volcanic ash.
Gulf Coast	Yields moderate to large amounts of fresh to slightly saline water. Near the coast, salt-water intrusion may cause water-quality deterioration. The aquifer is thicker (1,000-3,200 feet thick) and more productive in the eastern area, while around Corpus Christi it is 500-2,500 feet thick.	Sediments of Miocene through Holocene age	500-3,200	Sand, silt, gravel, and clay, with sandstone, volcanic ash, and tuffaceous clay. Caliche beds are present in the central and southern portions.
Edwards-Trinity (Plateau)	Yields small to large amounts of fresh to slightly saline water. Over the eastern portion, the aquifer yields far more water than is used. West of the Pecos River the reverse is true, and water levels are rapidly declining.	Georgetown, Edwards, and Comanche Peak Formations, and the Trinity Group of Cretaceous age	0-800	Cherty, gypsiferous, argillaceous, cavernous limestone and dolomite, with sand, silt, and clay. Gravel and conglomerate are usually found at the base.

Appendix B.—Hydrologic Units and Their Water-Bearing Properties—Continued

	Water-bearing properties	Geologic units	Aquifer thickness (feet)	Lithologic properties
MINOR AQUIFER				
Woodbine	Yields small to moderate quantities of fresh to slightly saline water. South of Dallas County the aquifer is thinner and the yields are lower.	Woodbine Group of Cretaceous age	100-600	Cross-bedded, ferruginous, tuffaceous sand, silt, clay, and lignite. More massive beds of sand and sandstone near the base.
Sparta	Yields moderate to large quantities of fresh to slightly saline water. Most production is from the northeast portion of the aquifer.	Sparta Formation of Eocene age	100-300	Sand interbedded with shale and clay. The more massive sand beds are near the base of the formation.
Queen City	Yields small to moderate supplies of fresh to slightly saline water. Yields are higher in the northeast portion.	Queen City Formation of Eocene age	100-500	Consolidated and unconsolidated cross-bedded sand, sandy shale, and clay with mica, glauconite, and limonite. The Sparta and Queen City are separated by a relatively thin glauconitic clay (50-100 feet) called the Weches Formation.
Edwards-Trinity (High Plains)	Yields small to moderate quantities of slightly to moderately saline water in the southern High Plains. Water occurs in the limestone only in the western portion of the aquifer.	Trinity and Fredericksburg Groups of Cretaceous age	0-300	Thin, locally discontinuous sand and sandstone overlain by clay, shale, caliche, and limestone.
Santa Rosa	In the eastern part, the aquifer yields moderate amounts of freshwater. In the western area, it yields moderate amounts of fresh to moderately saline water.	Santa Rosa Formation of Triassic age	100-700	Micaceous, cross-bedded sand with bituminous inclusions, interbedded with shale in the upper part. The eastern outcrop area has a basal conglomerate.
Hickory Sandstone	Generally yields moderate amounts of fresh to slightly saline water in the Llano Uplift area.	Hickory Sandstone of Cambrian age	100-500	Ferruginous sandstone with some shale near the top and conglomerate near the base.
Ellenburger-San Saba	Yields moderate amounts of fresh to slightly saline water in the Llano Uplift area.	Ellenburger Group and San Saba Formation of Cambrian and Ordovician age	400-2,000	Crystalline, cherty, sometimes sandy, limestone and dolomite, with some limestone conglomerate.
Marble Falls Limestone	Yields large amounts of fresh to slightly saline water in the Llano Uplift area.	Marble Falls Limestone of Pennsylvanian age	350-600	Dark cavernous limestone with some thin shale strata.
Blaine Gypsum	Yields small to large amounts of slightly to moderately saline water in Childress, Collingsworth, Cottle, Foard, Hardeman, King, and Wheeler Counties.	Blaine Formation of Permian age	200-300	Shale with lenticular, cavernous gypsum beds, dolomite, and some sandstone.
Igneous Rocks	Yields small to large amounts of freshwater in the Marfa-Alpine area. Elsewhere, in Jeff Davis, Presidio, Brewster, and Hudspeth Counties, yields are small.	Primarily extrusives of Tertiary age	0-4,000	Lava flows of rhyolite, trachyte, syenite, and basalt; tuffs, volcanic ash, breccia, unconsolidated sand, gravel, and silt.
Marathon Limestone	Yields small to moderate amounts of fresh to slightly saline water in the Marathon area of Brewster County.	Marathon Limestone of Ordovician age	350-900	Flaggy and dense, fractured, cavernous limestone, shale, conglomerate, and sandstone.

Appendix B.—Hydrologic Units and Their Water-Bearing Properties—Continued

	Water-bearing properties	Geologic units	Aquifer thickness (feet)	Lithologic properties
Bone Spring and Victorio Peak Limestones	Yields moderate to large quantities of slightly to moderately saline water, primarily in Hudspeth County.	Bone Spring and Victorio Peak Limestones of Permian age	1,300-2,000	Cavernous, cherty limestone, siliceous shale, clay, calcareous sand, and conglomerate.
Capitan Limestone	Yields moderate to large quantities of fresh to slightly saline water in West Texas.	Capitan and Goat Seep Limestones of Permian age	1,300-2,000	Reef limestone and back reef beds of limestone and dolomite with minor amounts of siltstone, sandstone, and evaporites.
Rustler	Yields moderate to large amounts of slightly to moderately saline water in Culberson, Reeves, and Ward Counties.	Rustler Formation of Permian age	200-500	Vugular and cavernous dolomite, limestone, and gypsum with a basal zone of sand, salt, conglomerate, and shale.
Nacatoch Sand	Yields moderate amounts of fresh to slightly saline water. In some areas, such as Hunt County, the aquifer is overdeveloped and partially dewatered.	Nacatoch Sand of Cretaceous age	350-500	Unconsolidated to indurated, massive, glauconitic, calcareous sand and marl.
Blossom Sand	Yields moderate amounts of fresh to slightly saline water in Fannin, Lamar, and Red River Counties.	Blossom Sand of Cretaceous age	0-400	Unconsolidated, ferruginous, glauconitic, sand, interbedded with sandy and chalky marl.
Purgatoire-Dakota	Yields moderate amounts of fresh to slightly saline water in Dallam County.	Purgatoire Formation and Dakota Sandstone of Cretaceous age	0-300	Sandstone, siltstone, and shale with some gravel.