A DIGITAL MODEL OF THE CARRIZO-WILCOX AQUIFER WITHIN THE COLORADO RIVER BASIN OF TEXAS

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TEXAS WATER DEVELOPMENT BOARD

JANUARY 1989

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A DIGITAL MODEL OF THE CARRIZO-WILCOX AQUIFER WITHIN THE COLORADO RIVER BASIN OF TEXAS

by

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TEXAS WATER DEVELOPMENT BOARD

IN COOPERATION WITH
THE LOWER COLORADO RIVER AUTHORITY
OF TEXAS

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TABLE OF CONTENTS

PAGE

PAGE

FIGURES

APPENDICES

* - These appendices are supplied with copy 1 of the report only. Copy 1 was given to the L.C.R.A. These appendices may be viewed at the offices of the Texas Water Development Board, Suite 305, 611 S. Congress Ave., Austin, Texas. Copies of the model documentation are available from the U.S. Geological Survey.

A DIGITAL MODEL OF THE CARRIZO-WILCOX AQUIFER WITHIN THE COLORADO RIVER BASIN OF TEXAS

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This study is a cooperative effort of the Texas Water Development Board and the Lower Colorado River Authority of Texas, and covers that area underlain by the Carrizo-Wilcox aquifer which occurs within the Colorado River basin. This includes most of Bastrop County, the northern one-third of Fayette County and small portions of Lee, Caldwell, and adjacent Counties.

The Carrizo-Wilcox aquifer is composed of the Wilcox Group and the Carrizo Sand of the Claiborne Group. The sand units yield most of the water and are interconnected, at least regionally, causing the entire system to act as a leaky artesian aquifer. The Carrizo Sand and Simsboro Formation dominate this system. The aquifer is essentially full and currently loses water through interformational flow to the overlying Younger Rocks, flow to the Colorado River where it crosses the outcrop, and rejected recharge in lower-lying portions of the outcrop area.

The chemical quality of water from the Carrizo-Wilcox aquifer within the study area is generally quite good although concentrations of most constituents increase with depth. Relatively high iron concentrations are often a problem within the area. The presence of iron is often unpredictable, with concentrations varying drastically both vertically and laterally in the aquifer.

The Carrizo-Wilcox aquifer is the major source of water for all uses in the study area. It contains very large amounts of water, and is capable of supplying well in excess of the projected demands in the study area until well beyond the year 2030.

Small amounts of water for rural domestic and livestock supply are pumped from shallower aquifers (Younger Rocks) in the downdip portion of the Carrizo-Wilcox. Few wells have been drilled to the Carrizo-Wilcox in this area because of the existence of these shallower aquifers, the absence of high demand resulting from low population density, and the depth of the Carrizo-Wilcox sands. Additional head data on the Carrizo in the downdip area would be beneficial to future modelling efforts.

Total estimated ground-water pumpage in Bastrop County during 1984 was 6,726 acre-feet, with 6,458 acre-feet from the Carrizo-Wilcox. Reported municipal pumpage was 5,634 acre-feet with 5,584 acre-feet from the Carrizo-Wilcox. As a result of increasing population, ground-water pumpage has risen, especially during the last 10 to 15 years. This trend is expected to continue, with total pumpage expected to reach 14,479 acre-feet in 2029 (Texas Water Development Board, 1984). Even this relatively high demand will not seriously stress the aquifer's potential, as long as reasonable constraints on well and wellfield spacing are met.

Precipitation on the outcrop is the major source of water to the aquifer. Computer simulations indicate that under present day conditions about three percent of the average annual rainfall enters the aquifer and passes downdip. Under these conditions, a significant amount of recharge enters the aquifer with the potential to be transmitted downdip but is rejected in the outcrop and along the course of the Colorado River. The computer simulations also suggest that systematic increases in pumpage from the aquifer would increase that amount of recharge retained in the aquifer, with drastic pumpage increases possibly increasing the amount of effective recharge to as much as about five percent of the annual rainfall.

Care should be taken in the planning, location, and construction of new wells and/or well fields. In the past, large capacity wells have been located too close to existing wells and well fields, resulting in interference between pumping wells. This has caused excessive local declines in the water table and losses of well pumping capacities.

The aquifer model which was constructed for this study works well to predict regional trends within the aquifer, and can be used for regional planning. It should not be applied to site specific problems or questions, however.

A DIGITAL MODEL OF THE CARRIZO-WILCOX AQUIFER WITHIN THE COLORADO RIVER BASIN OF TEXAS

INTRODUCTION

This report is the result of a jointly funded effort by the Lower Colorado River Authority and the Texas Water Development Board. In April, 1987, the LCRA requested that the Board conduct a study and construct an aquifer model of the Carrizo-Wilcox aquifer within the Authority's service area. Within this area, which includes most of Bastrop County and the northern portion of Fayette County, this major aquifer provides water for most municipal, industrial, domestic, and livestock use. In addition, the Colorado River crosses the recharge zone of the aquifer, and a complex interrelationship of both loss and gain occurs between the aquifer and the river. Since both the Authority and the Board are vitally interested in both ground and surface water availability and quality in this area, they entered into a cooperative agreement for the Board staff to use data from its recently completed ground-water study of the Carrizo-Wilcox aquifer in the Central Texas Area to construct a model of the aquifer.

Purpose and Scope

The major purpose of this study was the construction of a computer model of the Carrizo-Wilcox aquifer within the jurisdictional area of the LCRA. In general, this included location of all available well data within the study area; preparation of structural geologic maps for the various hydrogeologic layers, including those depicting formation tops, thicknesses, net sands, etc.; determination of the distribution of transmissivity, permeability, and storage; construction of a finite difference grid; input of data; calibration and verification of the model; and running the model using various future pumpage schemes to determine optimum development of the resource. Finally, this report was written to outline the findings of the study and serve as a handbook or user's manual for the model and/or other similar models.

Location and Extent of the Study Area

The study area is located just east-southeast of Austin and includes those portions of Bastrop, Fayette, Lee, and Caldwell Counties within the Colorado River Basin as well as additional portions of these and surrounding counties needed to provide for boundary considerations for the computer model. Therefore most of Bastrop County, the northwest one-third of Fayette County, the southwest one-third of Lee County, and the northeast one-third of Caldwell County are included in the study area and model (see Figure 1). The total areal extent is about 1,600 square miles. Elgin, Bastrop, Smithville, and Giddings are the largest cities within the study area. Smaller towns include Dale, McMahon, Cedar Creek, Red Rock, Bateman, Rosanky, Paige, McDade, Winchester, Westpoint, Cistern, Blue, and Mannheim.

Population and Economy

The population of Bastrop County was 24,726 in the 1980 census. This included 4,535 in Elgin, 3,789 in Bastrop, and 3,470 in Smithville. Giddings 1980 population was 3,950. It would be very difficult to determine the rural population of the study area outside of Bastrop County, but a rough estimate based on the relative area of each county within the study area to the total area of the county would be about 7,000. Population growth has been relatively steady in the larger cities in Bastrop County, especially since World War II. County totals had declined from the high of 26,845 in 1920, but showed a large rise between 1970 and 1980. The following table summarizes population changes in Bastrop County since 1900.

BASTROP COUNTY POPULATION

	1910	1920	1930	1940	1950	1960	1970	1980
Bastrop	1,707	1,828	1,895	1,976	3,176	3,001	3,112	3,789
Elgin	1,707	1,630	1,823	2,008	3,168	3,511	3,832	4,535
Smithville	3,167	3,204	3,296	3,100	3,374	2,933	2,959	3,470
County	25,344	26,649	23,888	21,610	19,622	16,925	17,297	24,726

The economy of the area is based primarily on agriculture and small businesses, including agribusiness, brick manufacturing, and electronic manufacturing. About 90 per cent of the agricultural income is from beef, dairy cattle, hogs, and poultry production. Much of the study area has been subject to development of rural housing for people working in Austin.

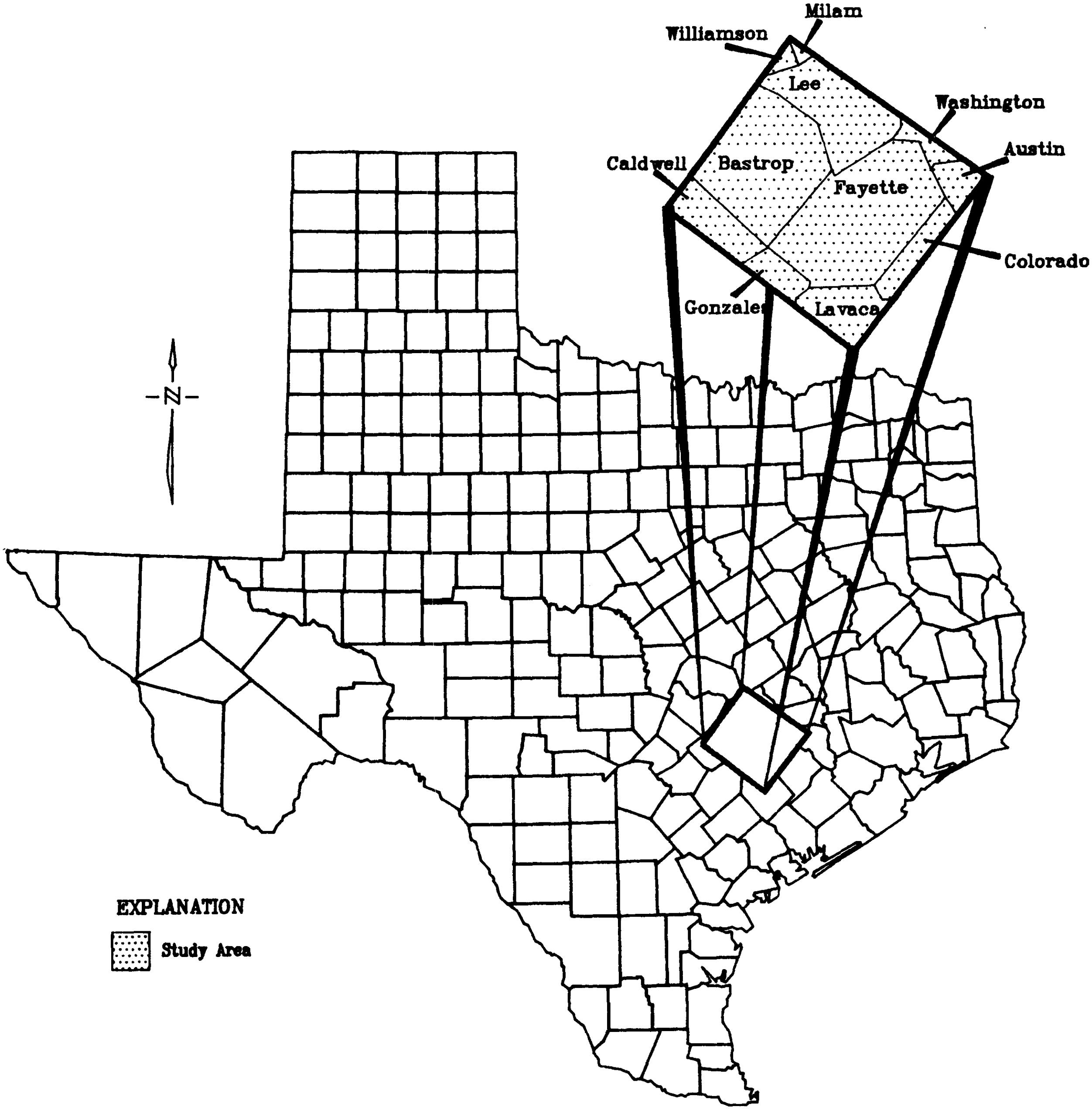

Figure 1
LOCATION MAP

Climate and Physiography

The study area has a dry subhumid climate in which the annual potential evaporation exceeds the annual precipitation. It is characterized by mild winters and hot summers with an average growing season of about 288 days. The annual precipitation at Smithville averaged 37.06 inches for the period 1917-1986 and ranged from 17.94 inches in 1956 to 59.38 inches in 1957. The average monthly precipitation for the same period ranged from 2.09 inches in August to 4.40 inches in May and averaged 3.06 inches. Actual monthly precipitation ranged from zero or a trace on several occasions to 23.20 inches in June 1940.

The average monthly gross lake-surface evaporation in the study area ranged from 2.5 inches in January to 8.7 inches in August for the period 1940-65 (Kane 1967, p. 86 and 97). Average monthly evaporation was 5.0 inches and the average annual evaporation was 60.3 inches. Actual monthly evaporation ranged from a minimum of 1.3 inches in February 1948 to a maximum of 11.6 inches in August 1951. Annually, the evaporation ranged from a minimum of 48.0 inches in 1942 to a maximum of 78.0 inches in 1956.

The normal annual temperature (1931-60) at Smithville was about 69 degrees F., with August being the hottest month and January the coldest.

Well-Numbering System

The well-numbering system used in this report is the one adopted by the Texas Water Development Board for use throughout the state. Under this system, each 1-degree quadrangle of Latitude and Longitude is given a number consisting of two digits ranging from 01 to 89. These are the first two digits appearing in the well number. Each 1-degree quadrangle is divided into 7-1/2-minute quadrangles which are given two-digit numbers from 01 to 64. These are the third and fourth digits of the well number. Each 7-1/2-minute quadrangle is further subdivided into 2-1/2-minute quadrangles given a single digit number from 1 to 9. This is the fifth digit of the number. Finally, each numbered well within a 2-1/2-minute quadrangle is given a two-digit number in the order in which it is assigned a number, starting with 01. These are the last two digits of the well number. Also, a two-letter prefix has been assigned for each county. This is AT for Bastrop County, RZ for Lee County, JT for Fayette County, and BU for Caldwell County. Thus, well AT-58-55-602 is in Bastrop County (AT), in the 1-degree quadrangle 58, in the 7-1/2-degree quadrangle 55, in the 2-1/2-degree quadrangle 6, and was the second well numbered within the 2-1/2-degree quadrangle (see Figure 2). The 7-1/2-degree quadrangles used in the numbering system are equivalent to the United States Geological Survey's 7-1/2-degree Topographic Maps.

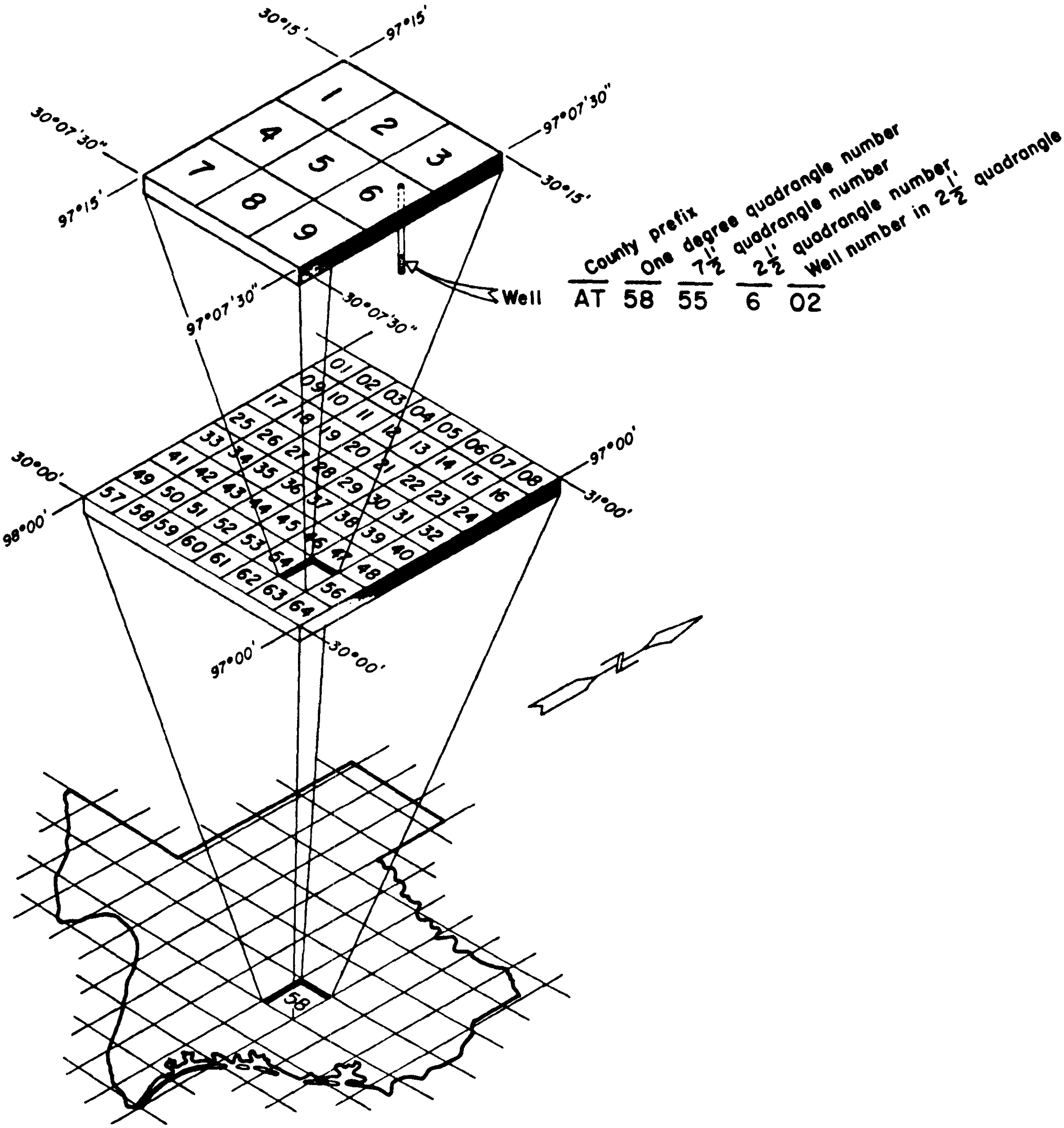

Figure 2
WELL-NUMBERING SYSTEM

Acknowledgements

The authors express their thanks to the many people who provided aid and information for the study. These include, but are not limited to personnel, of the many city water departments and water supply corporations, employees of the LCRA, especially, Dr. Quentin Martin, and many landowners and water-well drillers. Without the help of such people no ground-water study could ever be completed.

This study was completed under the supervision of Dr. Tommy Knowles, Chief of the Water Availability Data and Studies Section and Mr. Henry J. Alvarez, Head of the Ground-Water Unit.

GENERAL GEOHYDROLOGY

Structurally, the modeled area is located in the Gulf Coast Interior Basin, within the southern extension of the East Texas Basin (see Figure 3). The East Texas basin was formed during early Triassic time. Deposition in the basin began during the Triassic and continued throughout the Mesozoic Era and into Tertiary time (Nicholls and Others, 1968). A total of more than 20,000 feet of sediments were deposited, consisting mainly of marine evaporites, carbonates, and clastics (Fogg and Kreitler, 1982). Fluvial, deltaic, and marine deposits of Eocene age are at the surface throughout the study area, and it is these younger rocks which contain fresh water and make up the Carrizo-Wilcox and overlying aquifers which we are modeling in this study (see generalized geologic section with model layers, Figure 4, and geologic cross sections, Figures 5 thru 10. For location of cross sections, see Figure 1, Appendix 5.) As indicated on cross sections and geologic maps of the area, faulting occurs within the study area which may effect the flow of water within the Carrizo-Wilcox aquifer to some small extent, at least locally. This faulting is a part of the Mexia-Talco-Luling fault trend, and mostly is located along or near the outcrop of the Carrizo sand in this area. For the purposes of this model, we have divided these units into five layers which are described briefly below.

Younger Rocks

All of the formations within the study area which are younger than the Carrizo sand are grouped into Layer One of the model. These consist of the upper part of the Claiborne Group and most of the Jackson Group (see Figure 4). These units were deposited in regressive fluvial-deltaic and transgressive marine environments (Fisher, 1964; and Fogg and Kreitler, 1982). The younger units are exposed over much of the study area, and the sandy parts form minor fresh-water and fresh-to-slightly saline water aquifers which include the Queen City, Sparta, and Jackson Group aquifers.

These younger water-bearing units are generally of fluvial-deltaic origin. They dip toward the coast at less than 100 feet per mile in their outcrop areas to about 200 feet per mile downdip and are primarily composed of unconsolidated sands and muds (see Figure 4). The interbedded marine transgressive units are composed of clays and shales but locally contain discontinuous sands, making the entire layer act as a leaky artesian aquifer system (Fogg and Kreitler, 1982). Production capacities of wells completed in the Younger Rocks range from a few gallons per minute (gpm) up to a few hundred gpm, but most known wells completed in these aquifers produce small amounts of water for rural domestic and livestock uses.

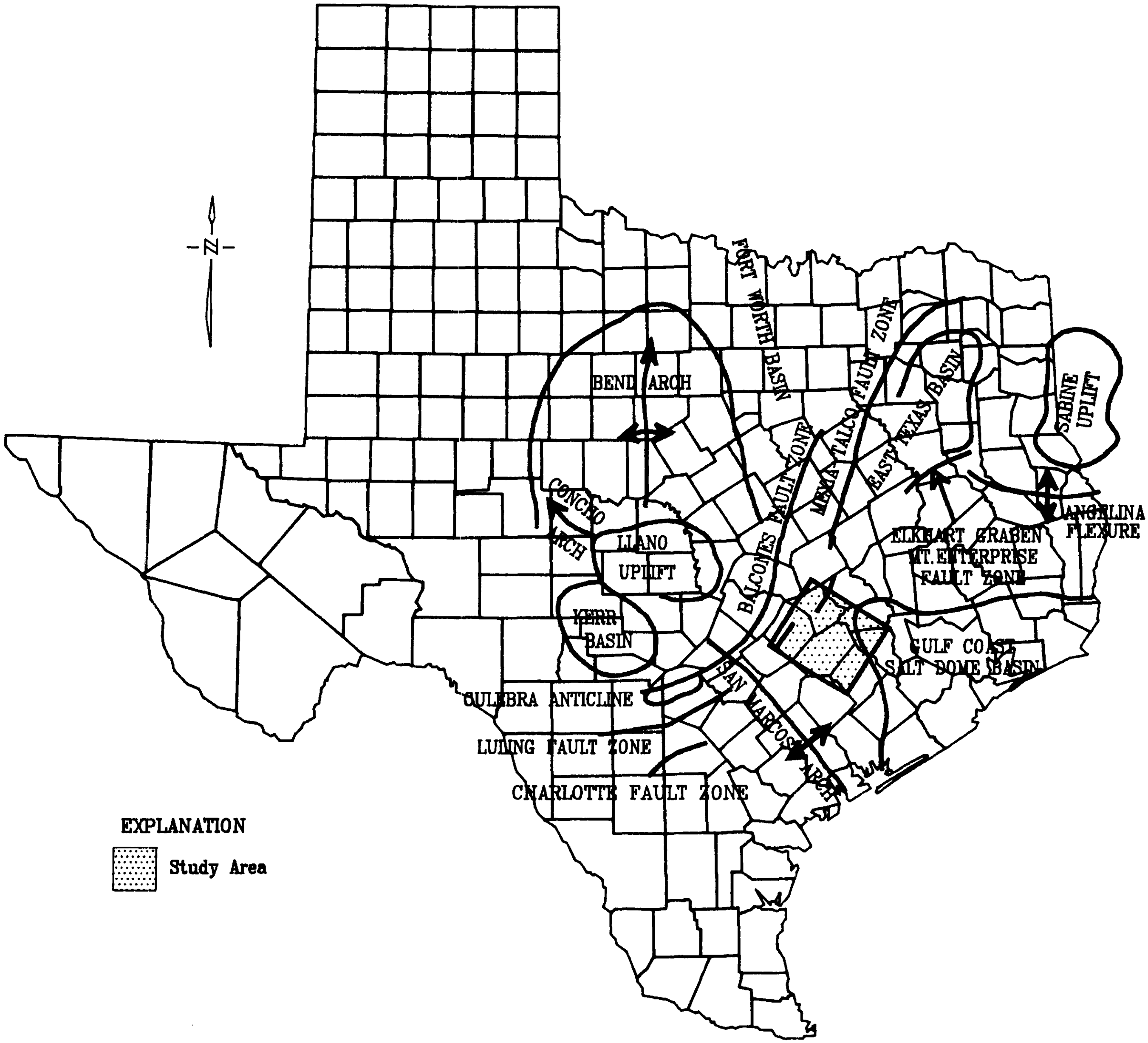

Figure 3

MAJOR STRUCTURAL FEATURES
IN EAST AND CENTRAL TEXAS

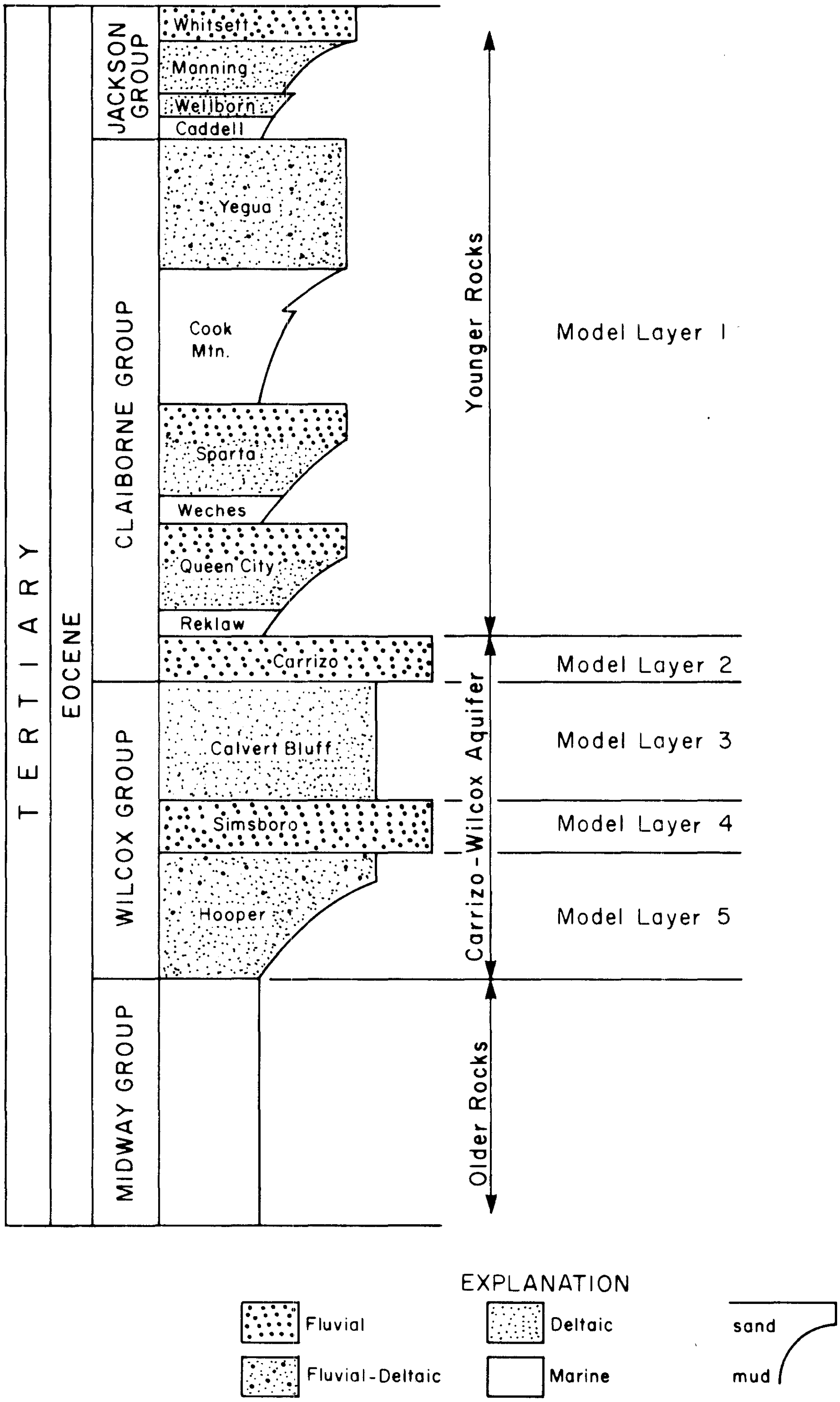

Figure 4
Generalized Geologic Section with Model Layers

Carrizo-Wilcox Aquifer

Layers Two, Three, Four, and Five of the model represent the Carrizo Sand, which is the lowermost part of the Claiborne Group and the three formations of the Wilcox Group: the Calvert Bluff, Simsborcl, and Hooper formations respectively (see Figure 4). Together, these units make up the Carrizo-Wilcox aquifer, one of the majcr aquifers of Texas.

Carrizo Sand

Layer Two is the Carrizo Sand which is of fluvial origin and generally consists of fairly homogeneous fine-to-medium grained sands with minor amounts of inter-bedded clays. This unit extends across Texas and reaches a maximum thickness of more than 400 feet in the study area. Its average thickness is less than 300 feet, however. The Carrizo dips into the subsurface beneath the You:nger Rocks at less than 100 feet-per-mile near the outcrop, but dip increases to more than 200 feet-per-mile further down dip. In some portions of the area, faulting has effected the Carrizo outcrop and may also **affect the** flow of water within the aquifer, at least locally. It would be very difficult to quantify the effects of this faulting, however, and it was not possible within the confines of this project. The Carrizo Sand has the capacity to produce relatively large amounts of water throughout much of the study area and a few large capacity wells are producing from this formation. In much of the downdip area, however, lower capacity, but much shallower wells can be completed within the Younger Rocks and therefore most wells are not drilled on into the deeper aquifers.

Calvert Bluff Formation

This is the youngest of the three formations which make up the Wilc:ox Group and consists of fine-to-coarse grained sands and sandstones interbeddedwithmudstones, ironstone concretions, and discontinuous beds of lignite. It was laid down during a period of cyclic fluvial and deltaic deposition with thicknesses averaging less than 500 feet, but ranging up to over 1,000 feet These deposits also dip southeastward toward the coast under the Carrizo Sand and Younger Rocks at rates similar to those of the Carrizo. The Calvert Bluff is Layer Three in the model. In isolated portions of the study area, where thicker sands occur within the formation, some higher capacity wells have been constructed. Generally, however, wells completed in the Calvert Bluff produce relatively small amounts of water for domestic and livestock uses.

Simsboro Formation

The Simsboro Formation is Layer Four of the model. It consists of fine-to-coarse grained sands with only small amounts of interbedded clay, mudstone, and mudstone conglomerate. Deposition occurred in a fluvial environment associated with downdip deltaic deposition. Sand deposits of this formation are well developed and easily discernable both on the surface and in well logs in the northern part of the study area. In the southern portion of the area, however, starting at about the Colorado River, this portion of the Wilcox Group contains less and less sand and the boundaries between the Simsboro and the under-lying and over-lying formations become less pronounced. Within the study area, the Simsboro ranges in thickness from about 100 to 300 feet. Because of the complex nature of this formations' structure and deposition, dips vary greatly locally, but in general the Simsboro's dip is similar to that of the other portions of the Carrizo-Wilcox aquifer. Most major wells in this area are completed in the Simsboro Formation.

Hooper Formation

Layer Five of the model is the Hooper Formation, which is the oldest unit of the Wilcox Group. The Hooper is mostly made up of mudstones with relatively small amounts of interbedded fine-to-medium grained sandstone. Thickness of this formation may range up to about 1,300 feet in the deep subsurface, but is generally less than 500 feet. The Hooper sediments dip to the southeast at from less than 100 to about 200 feet per mile. Generally, this formation provides only relatively small amounts of water for domestic and livestock uses within the study area.

Older Rocks

Underlying the Hooper Formation throughout Texas are interbedded shales, clays, and limestones belonging to the Midway Group of Eocene age. This group dips toward the coast at rates similar to those of the overlying rocks and in general provides a barrier to downward ground-water flow. On the outcrop of the Midway, a few isolated wells produce small amounts of fresh-to-slightly saline water for rural domestic and livestock use from thin erratic lenses of sand, however.

GENERAL GROUND-WATER HYDROLOGY

Hydrologic Cycle

The hydrologic cycle is the sum total of the processes and movements of the earth's moisture from the sea, through the atmosphere, to the land, and eventually, with many numerous delays en route, back to the sea. All water occurring in the study area is derived from precipitation. That portion of the water available for man's use--whether from direct precipitation, streamflow, lakes, water from wells, or spring discharge--is merely captured in transit, and after its use and/or reuse, is returned to the hydrologic cycle (Figure 11).

Source and Occurrence of Ground Water

The ultimate source of almost all ground water is precipitation, either through direct infiltration on the outcrop, loss from streams and lakes where they occur over the outcrop, or through seepage or leakage from rocks above or below the aquifer. That small portion of the total precipitation which seeps down through the soil mantle and reaches the saturated zone within an aquifer is called ground water.

Ground water is said to occur under either water-table (unconfined) or artesian (confined) conditions. Under water-table conditions, the top of the saturated zone is exposed only to the pressure of the atmosphere. When a well taps a water-table aquifer, the water in the well bore will not rise above the point at which it was encountered. Artesian conditions exist when the aquifer is bounded on top by an impervious bed and the water is under hydrostatic pressure. When a well taps an artesian aquifer, the water in the well bore will stand at some point above the top of the aquifer, and if the land surface at the well is sufficiently lower than the land surface at the aquifer's outcrop (recharge) area, the water will flow. Ground water in the Carrizo-Wilcox aquifer in the study area occurs under both water-table and artesian conditions. Because most of the horizontal boundary zones within the aquifer have significant permeabilities, however, much of the Carrizo-Wilcox is generally classified as leaky artesian.

Recharge, Movement, and Discharge of Ground Water

Recharge to the Carrizo-Wilcox is by natural means. The source is precipitation and the major controlling factor is its frequency and intensity. Other significant factors controlling recharge include topography, amount and kind of vegetative cover,

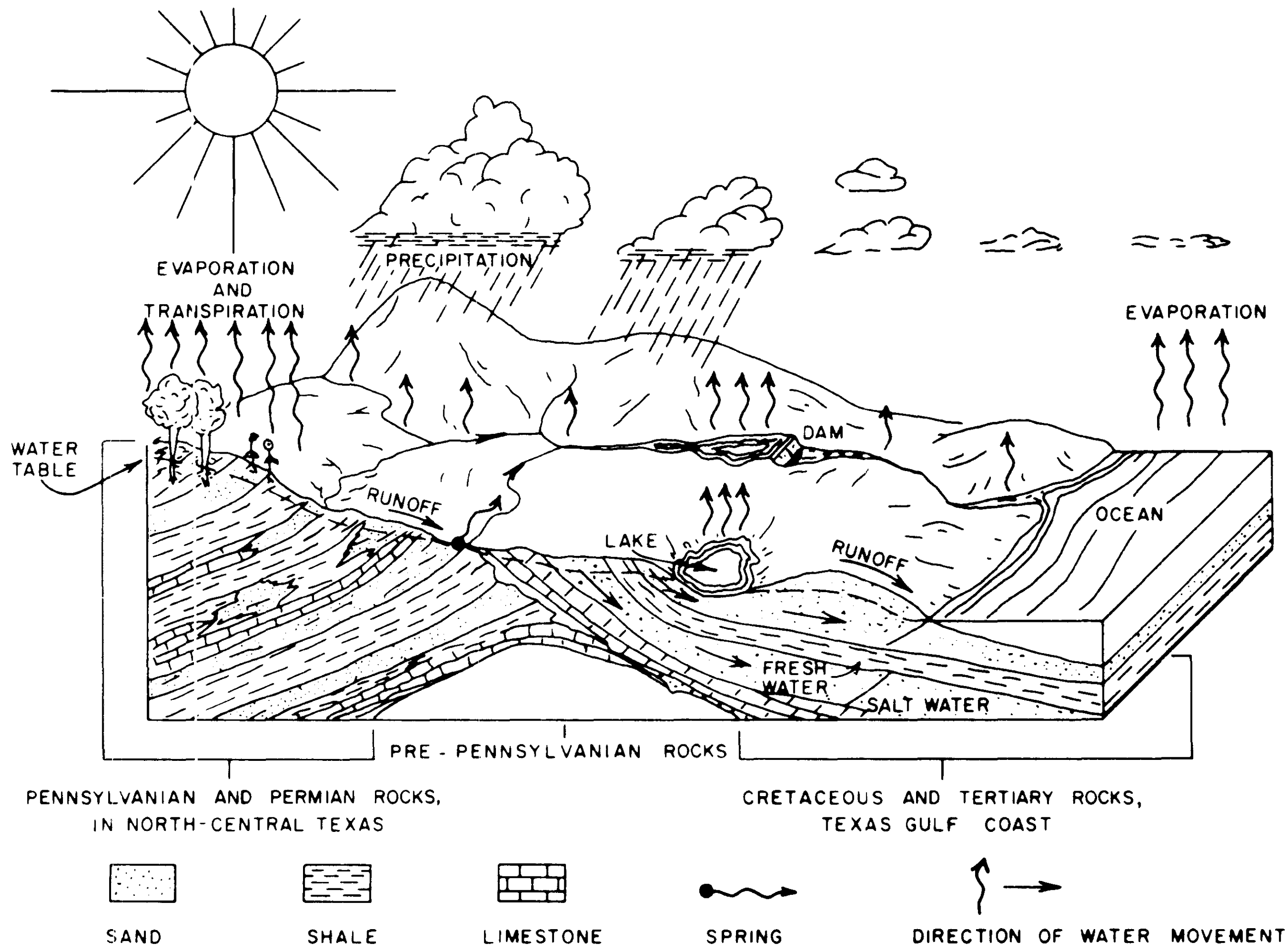

Figure 11 —Hydrologic Cycle

soil characteristics, and hydraulic conductivity of the rocks and soils involved. Seepage from lakes and streams on the aquifer's outcrop and interformational leakage also contribute to recharge of the Carrizo-Wilcox aquifer. Minor amounts of artificial recharge might be accomplished in this area by storing runoff water and allowing it to run over the aquifer's permeable outcrop or by adding the water through recharge wells. Some filtering and/or other treatment of input water might be required for longterm operation, however.

If recharge is less than discharge over a significant period of time, an aquifer will be progressively drained. If recharge is greater than discharge, then water is taken into storage and will progressively fill the aquifer. Within the study area, the Carrizo-Wilcox Aquifer is nearly full, and currently takes in only a limited amount of recharge. All but a small portion of precipitation on the outcrop either runs off on the land surface, is evaporated or transpired by plants, or is rejected in lowlying areas within the outcrop through seeps and springs. That portion of recharge that enters an aquifer and is transmitted downdip is often referred to as effective recharge. The natural rate of effective recharge to the Carrizo-Wilcox aquifer is estimated, using computer simulation, to average just over one inch per year within the study area. This is approximately three per cent of the average annual precipitation rate. Computer simulations indicate that effective recharge to the aquifer in the outcrop, as well as interformational leakage from the overlying younger beds, can be increased through additional pumpage from the Carrizo-Wilcox. These model simulations with higher pumpage indicate that effective recharge in the outcrop might be increased to over five per cent of the mean annual rainfall, while leakage of water into the Carrizo-Wilcox from the younger formations could exceed the effective recharge on the outcrop. Leakage of significant amounts of water from the overlying Younger Rocks through the Reklaw formation into the Carrizo Sand could cause some deterioration of water quality within the Carrizo-Wilcox, at least locally, due to increased concentrations of iron derived from the Reklaw.

Movement of ground water within the Carrizo-Wilcox aquifer is from areas of higher head or pressure to areas of lower head or pressure. Within the outcrop this is mainly controlled by topography. Water that enters the aquifer in areas of higher elevation moves generally downdip within the sand units but also may move laterally toward the drainageways and valleys. Much of this water is lost from the aquifer through evaporation and transpiration or is rejected through seeps and springs. Relatively small amounts, as indicated above, continue downdip into the confined part of the aquifer. Here, depending on relative hydrostatic pressure between various parts of the Carrizo-Wilcox aquifer and the overlying formations, the water may move vertically either up or down. Results of this study as well as others on the Carrizo-Wilcox in Texas indicate that the major component of vertical movement is upward, especially in the far downdip parts of the aquifer. The rates of movement within the Carrizo-Wilcox aquifer in the study area, both vertically and horizontally, are highly variable, depending on such things as sand-body distribution, differential hydraulic conductivity, and differences in hydraulic gradient. The highest velocities occur in areas with the largest accumulations of conductive sands. Such sands are usually associated with the Simsboro and Carrizo. Water velocities in similar sands as estimated by other workers have ranged from a few feet to as much as several hundred feet per year (Thompson, 1966, and Guyton, 1972). Locally, pumping of wells and well fields can alter both the direction and velocity of ground-water movement, almost always increasing the speed of movement toward the center of pumpage.

Discharge is the sum of those processes which remove water from an aquifer, and may be by both natural and artificial means. Natural discharge occurs as underflow to rivers and lakes, flow from springs and seeps, interformational leakage, transpiration by plants, and by evaporation. Within the project area, study of water level maps indicates that the Colorado River and its major tributaries appear to be receiving a major portion of the natural discharge from the Carrizo-Wilcox aquifer. The major artificial discharge process is pumpage from wells.

Hydraulic Properties of the Aquifer

The hydraulic properties of an aquifer are usually expressed in terms of its coefficients of permeability, transmissivity, and storage. These are determined by the porosities and hydraulic conductivities of the sediments which make up the aquifer and control the aquifer's capacity to yield water to wells. These parameters can be determined or at least approximated, by conducting controlled pumping tests of wells. Since these coefficients are a measure of an aquifer's ability to store and transmit water, they can be used to determine proper well spacing, interference between pumping wells, and to predict water-level drawdowns around pumping wells. Calculation or estimation of these parameters and their variability both horizontally and vertically through the aquifer is essential in constructing a workable aquifer model.

Due to the complex lithologic make up of the Wilcox Group, hydraulic conductivities are highly variable from one area to another. The highest values are found in areas where channel sands are present. Within these areas, hydraulic conductivities generally ranged from 20 to 60 feet per day. Much lower values, generally ranging from three to seven feet per day, were found in the areas of interchannel deposition (Henry, Basciano, and Duex, 1980). By comparison, the Carrizo Formation is lithologically more uniform, and therefore has more consistent hydraulic conductivities. A significant range still existed, however. The values are similar to those associated with Wilcox channel sands.

Coefficients of storage for the Carrizo-Wilcox in the study area ranged from 0.00001 to 0.001 in the artesian portion and from 0.05 to 0.3 in the water-table areas. These are general ranges derived from many laboratory studies on materials from all types of aquifer systems (Ferris, et al, 1968). The potential yield to a well completed in an aquifer is largely determined by the hydraulic properties of the aquifer. Within the study area, yields of wells completed in the Carrizo-Wilcox range from a few gallons per minute to over one thousand gpm, partially because of the construction and completion of the wells but also due to some extent to the variable nature of the aquifer. A well completed with screens opposite all of the water-bearing sands of the aquifer might have a potential yield of several thousand gpm, especially if located in a downdip area with thick sands in the Simsboro, Calvert Bluff, and Carrizo.

Fluctuations of Water Levels

Ground-water in the Carrizo-Wilcox aquifer exists under both water-table and artesian conditions. Water-table conditions occur within the outcrop area and the static water levels in a well indicates the position of the water table at that well. Artesian conditions, which occur within the Carrizo-Wilcox aquifer through the majority of the study area, are caused by the aquifer being overlain by confining beds of lower hydraulic conductivity. This condition produces hydrostatic pressures which in turn cause water levels to rise in well bores above the top of the aquifer. Artesian water levels define the position of the aquifer's potentiometric surface (see Figure 2, Carrizo-Wilcox water level map, in Appendix 5).

Fluctuations in the water table can be both regional and local in nature. Small scale daily fluctuations may be in response to earthquakes, tidal forces, or changes in barometric pressure. Seasonal climatic changes may play an important role in regional fluctuations, generally showing the highest water levels in late winter and early spring and the lowest in late summer and early fall. Long term changes in recharge or discharge, however, generally cause the most significant fluctuations.

Pumpage from wells causes significant fluctuation of water levels. Depending on the hydrologic characteristics of the aquifer and the rate of water withdrawal, various sizes of cones of depression are formed around pumping wells or well fields. These cones are formed by the drawdown of the water table or potentiometric surface. The cones will expand until they reach a recharge source equal to the discharge rate. When several adjacent wells are too close together, their respective cones of depression may overlap and large areas of water level decline may result (Figure 12). When local or regional pumpage exceeds the aquifer's capacity to store and/or transmit water, water level declines and reduced pumping rates are usually the result.

In the study area, and in fact throughout the central Texas extent of the Carrizo-Wilcox aquifer, there has been little historical evidence of significant regional declines in the potentiometric surface of the aquifer. In a few areas where several relatively high capacity wells have been located in close proximity: the City of Elgin's well field and the Camp Swift well field, for example; local cones of depression have resulted. All available data indicate, however, that even in these local severe cones recovery rapidly follows cessation or even significant reduction in pumpage.

Water levels measured in wells completed in the various layers of the Carrizo-Wilcox aquifer in the central Texas area show only minor differences between layers, at least regionally. For this reason, water levels from all of the layers were combined on one water-level map for use in this and previous studies. In fact, this is one of the reasons that the two geologic units historically have been combined into one aquifer by hydrologists working in Texas. As stated above, most water-level measurements in wells located at reasonable distances from other high capacity wells have remained relatively constant. The magnitude of such distances depend on hydrologic conditions and hydraulic characteristics in the aquifer at the specific location, but in the Carrizo-Wilcox, will generally range from about 1,200 to 2,000 feet between individual high capacity wells. Distances between major producing well fields should be measured in miles, at least.

CHEMICAL QUALITY

Almost all Carrizo-Wilcox wells inventoried in the study area produce fresh to slightly saline water. The southeastern boundary of the model and the study area is delineated by the approximate downdip limit of slightly saline water in the Carrizo Sand (refer to the location map, Figure 1). To a certain extent, the water contained in each individual unit within the Carrizo-Wilcox aquifer becomes saltier with depth (downdip.) Therefore, if wells were to be drilled into the Wilcox in the downdip part of the area the water encountered would probably be moderately saline. Water produced from wells completed in the Younger Rocks ranged from fresh to moderately saline.

These limits are those in general use in ground-water hydrology and are as follows:

CATEGORY	DISSOLVED SOLIDS CONTENT
FRESH	less than 1,000 MG/L
SLIGHTLY SALINE	1,000 to 3,000 MG/L
MODERATELY SALINE	3,000 to 10,000 MG/L
SALINE	over 10,000 MG/L

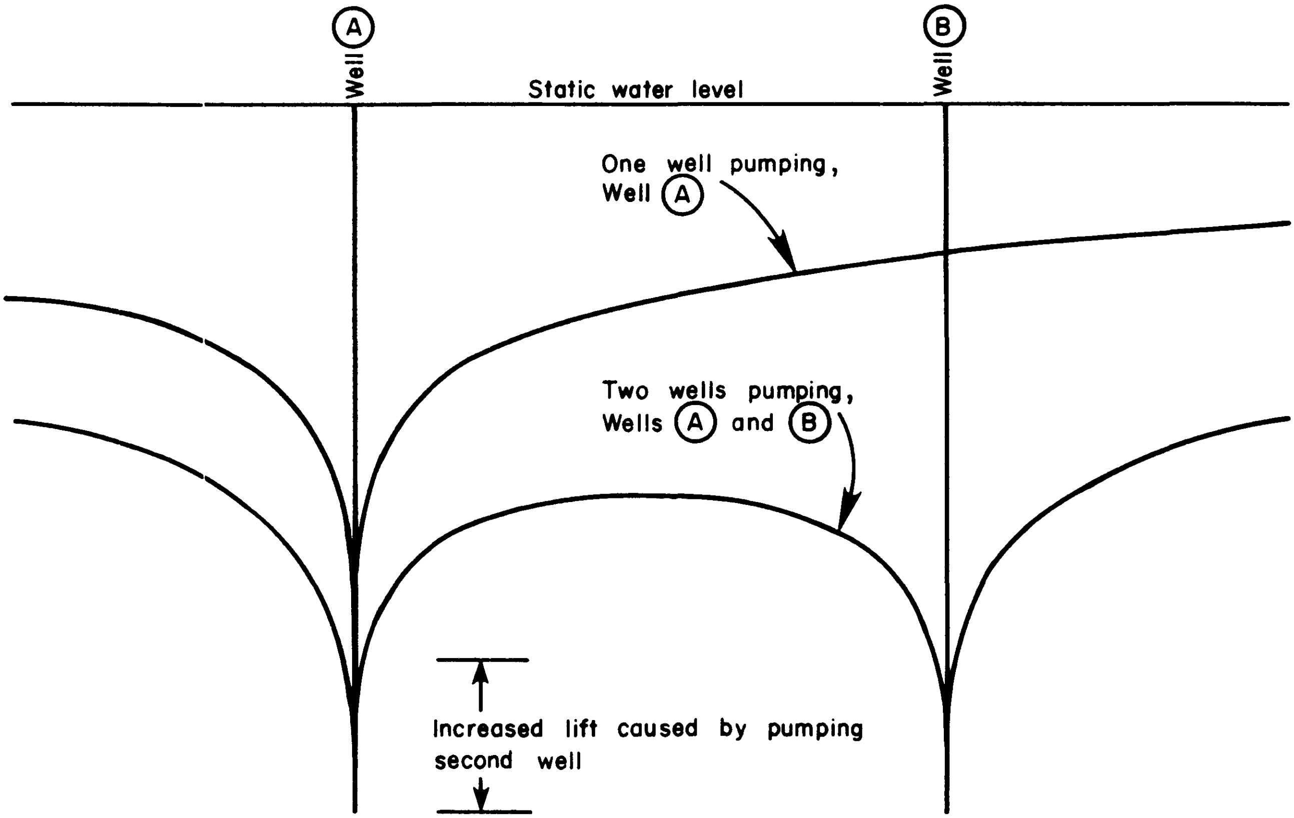

Figure 12—Idealized Cross Section Showing Drawdown Interference Between Two Pumping Wells

The only significant water quality problem in the study area is the erratic occurrence of sands containing water with high concentrations of iron. While there are a few isolated areas where almost all wells produce high iron water, in most cases it is difficult, if not impossible, to predict the iron concentration until the well is completed and samples collected and analyzed. This is further complicated by the fact that iron concentration varies not only from area to area, but vertically within the same well from sand bed to sand bed within the aquifer. Since it is difficult and expensive to collect samples for chemical analysis from every sand interval encountered when drilling a test hole or well, the quality of the water finally produced often depends on chance in properly selecting the intervals to be screened. Fortunately, high iron concentrations in water can be reduced by several relatively inexpensive methods, including aeration, addition of chemicals, et cetera, and the iron removed by settling, or filtration. Municipalities and industries with water having high iron concentrations usually apply such methods to their water systems. While similar relatively inexpensive methods could be used in small domestic systems, there is little such use currently.

GROUND-WATER USE

Most water use in Bastrop County and the immediately surrounding area of Lee, Fayette, Caldwell, and Gonzales Counties is from ground-water sources. With the exception of Fayette County, the Carrizo-Wilcox aquifer provides a large majority of the total used. While a few wells have been drilled to the Carrizo within Fayette County, none are currently pumped. Within the study area, ground water is used for almost all public, rural domestic, and livestock supplies, as well as most industrial and irrigation supplies. The only known major use of surface water in the area is for cooling purposes in the generation of electricity, though there is some use for gravel washing and irrigation, and very minor use for rural domestic and livestock supply. Data for the following analysis of ground-water pumpage was prepared by the personnel of the Board's Water Uses, Projections, Environmental and Conservation Section, and includes information provided by the individual cities, industries, and irrigators in the area.

This pumpage data is presented in the following tables.

BASTROP COUNTY
GROUND-WATER PUMPAGE
(acre-feet)

YEAR	MUNICIPAL	INDUSTRIAL	IRRIGATION	RURAL DOMESTIC AND LIVESTOCK	TOTAL
1962	1,061	150	200	860	2,300
1963	1,281	150	380	860	2,700
1964	1,218	150	1,500	860	3,700
1965	1,149	150	1,900	860	4,100
1966	1,189	150	1,900	860	4,100

YEAR	MUNICIPAL	MANUFACTURING	LIVESTOCK	IRRIGATION	STEAM ELECTRIC	MINING	TOTAL
1980	3,958	76	616	749	0	0	5,399
1984	5,634	133	624	325	0	10	6,726

ADJACENT COUNTIES
GROUND-WATER PUMPAGE
(acre-feet)

YEAR	MUNICIPAL	MANUFACTURING	LIVESTOCK	IRRIGATION	STEAM ELECTRIC	MINING	TOTAL
CALDWELL COUNTY							
1980	2,194	0	169	100	0	0	2,463
1984	2,466	0	82	205	0	3	2,756
GONZALES COUNTY							
1980	1,626	0	1,966	600	0	0	4,192
1984	1,435	90	377	1,089	0	18	3,009
LEE COUNTY							
1980	1,958	0	646	250	0	2	2,856
1984	2,447	0	590	35	0	0	3,072

That part of the above table for Bastrop County, 1962 through 1966 is from TWDB Report 109 (Follett, 1970); the figures for 1980 and 1984 were derived by Ground Water Unit staff from data secured from the Board's Municipal, Industrial, and Irrigation pumpage Inventories.

In 1985 an estimated total of 6,354 acre feet of ground water was pumped for all purposes in Bastrop County. Of this, 6,098 acre feet was estimated to be from the Carrizo-Wilcox aquifer. This compares to the 1962 total pumpage of 2,300 acre feet, again with nearly all from the Carrizo-Wilcox aquifer. In 1984 estimated municipal pumpage totaled 6,726 acre feet, with 6,438 acre feet from the Carrizo-Wilcox. In the adjacent counties, the percentage of ground-water pumpage from the Carrizo-Wilcox in 1980 was 90 percent in Caldwell County, 75 percent in Gonzales County, and 32 percent in Lee County. In 1984, it was 86 percent in Caldwell County, 73 percent in Gonzales County, and 62 percent in Lee County.

Municipal Pumpage

During 1962, an estimated total of 1,061 acre feet of ground water was pumped by cities and water supply districts for municipal use in Bastrop County. Well over half of this total was produced from the Carrizo-Wilcox aquifer. In 1980 and 1984, the total pumpage for municipal purposes was 3,958 and 5,634 acre feet, respectively, with 2,632 and 5,584 acre feet or 66.5 and 99.1 percent provided by wells completed in the Carrizo-Wilcox aquifer.

In 1960, the major producing entities within the study area were the Cities of Bastrop, Elgin, Giddings, and Smithville. After 1979, Aqua Water Supply Corporation became a major supplier, and in 1985, took over the City of Bastrop's well field at old Camp Swift and began supplying water for the majority of that city's use. In addition, Aqua supplies water to a large part of the rural domestic users throughout Bastrop County and in much of the contiguous area in Lee, Fayette, Gonzales, Caldwell, Travis, and Williamson Counties. Based on the number of customers served, Aqua is currently the largest Water Supply Corporation in Texas.

The following table, which shows 1970 through 1986 groundwater pumpage (in acre-feet) by the Aqua Water Supply Corporation and the four largest Cities in the study area, illustrates the increase in pumpage for this use.

MUNICIPAL PUMPAGE
(in acre-feet)

YEAR	BASTROP	ELGIN	GIDDINGS	SMITHVILLE	AQUA W.S.C.
1970	557.6	650.3	750.6	359.3	--
1971	991.1	494.2	682.6	412.3	--
1972	992.1	539.3	427.0	387.8	--
1973	1,343.7	566.3	543.7	292.2	--
1974	1,340.6	225.3	919.4	292.2	--
1975	1,530.9	569.0	1,016.9	446.5	--
1976	1,378.6	421.7	416.4	510.7	--
1977	1,679.2	450.2	1,323.4	308.4	--
1978	1,753.9	470.5	637.0	566.8	--
1979	961.8	484.3	616.2	549.6	1,075.4
1980	922.4	588.6	904.2	742.7	1,434.4
1981	901.9	526.6	792.7	683.8	1,367.1
1982	1,304.0	653.1	864.3	747.2	1,633.0
1983	1,366.7	621.1	827.4	613.2	1,933.6
1984	1,390.0	836.6	1,006.0	648.4	2,469.2
1985	62.7	1,075.9	1,067.5	558.5	3,551.6
1986	0.0	1,126.3	1,200.0	378.7	3,474.5

The 1980 and 1984 figures for municipal pumpage from the Carrizo-Wilcox were used as input for a series of model simulations of the aquifer. Other, higher estimations of future pumpage for municipal use were also used, including the "high use" or drought condition estimates from the last update of the State Water Plan.

Irrigation Pumpage

Relatively limited amounts of ground water are used in the study area for irrigation. During most years there is adequate rainfall for the types of crops grown in this area. In addition, the rolling topography limits large scale irrigation. Therefore, while in some years there has been a significant increase in irrigation pumpage, it is probably due more to lack of rainfall during some dry years than to an increase of crop acreage. The following table (Texas Water Development Board, 1986) shows irrigation acreage, pumpage, and wells for Bastrop County.

YEAR	ACREAGE	PUMPAGE (acre-feet)	WELLS
1958	65	45	2
1964	270	237	6
1969	1,097	733	11
1974	927	927	12
1979	0	0	10
1984	484	325	6

Rural Domestic and Livestock Pumpage

In the past, an estimated 95 percent of water for rural domestic and livestock use within the study area was produced from ground-water sources and pumped from small capacity private wells. The other five percent was surface water pumped from the Colorado River and from small stock tanks or ponds. In a ground-water study of Bastrop County conducted by the U.S.G.S. and published in 1970, total pumpage of ground water for these uses was estimated at 860 acre-feet per year for the period from 1962 through 1968. Recent Board estimates indicate that within the study area about 90 percent of water for rural domestic purposes and a significant part of livestock supply water is provided by water supply corporations, cities, and water districts. This is still from ground-water sources, however, and mostly from the Carrizo-Wilcox aquifer. Bastrop County continues to produce considerable income from beef and dairy cattle, accounting for most of the 616 acre-feet estimated pumped in 1980 and the 624 acre-feet estimated pumped in 1984 for livestock supply. About half of these totals was estimated to have come from wells producing from the Carrizo-Wilcox aquifer. The rest comes from aquifers which are a part of the Younger Rocks as discussed previously. Adjacent counties have similar patterns of ground-water use for livestock supply, but there is no use from the Carrizo-Wilcox in Fayette County.

Industrial Pumpage

Pumpage of ground water for industrial uses is very minor in the study area. Most of the industrial water pumped is for mining purposes and use in brick manufacturing.

THE MODEL

Theory

The primary objective of this study was to develop and construct a digital model of the Carrizo-Wilcox aquifer within the jurisdictional area of the L.C.R.A. This model is to be used as a management tool by the Authority to evaluate the regional water-supply capabilities of the aquifer within the Colorado River basin. For this purpose we chose to use the finite-difference model and associated modular computer program developed by M. G. McDonald and A. W. Harbaugh of the U. S. Geological Survey. It is documented in U.S.G.S. Open-File Report 83-875, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. The model has a main program and a series of highly independent subroutines or modules. Each subroutine package enables the user to deal with a specific feature of the hydrologic system which is to be simulated. Major options presently available include procedures to simulate the effects of wells, rivers, drains, evapotranspiration, and general-head boundaries. Using this model, a modular, five layer, three-dimensional finite-difference ground-water flow model was constructed which covered the study area.

Derivation of the Finite-Difference Equation

McDonald and Harbaugh (1984) used the following partial-differential equation to describe the three-dimensional movement of ground water of constant density through porous earth material:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where

x, **y**, and **z** are cartesian coordinates aligned along the major axies of hydraulic conductivity K_{xx}, K_{yy} , K_{zz};

h is the potentiometric head (L);

W is a volumetric flux per unit volume and represents sources and /or sinks of water;

S_s is the specific storage of the porous material (L^{-1});

t is time (t).

In general, S_s ,K_{xx}, K_{yy}, and K_{zz} may be functions of space (S_s = S_s (x, y, z), and K_{xx} = K_{xx}(x,y,z, etc.) and **h** and **W** may be functions of space and time (**h** = **h**(x,y,z,t), **W** = **W**(x,y,z,t)) so that the equation above describes ground-water flow under nonequilibrium conditions in a heterogeneous and anisotropic medium. This equation, together with specification of initial-head conditions, constitutes a mathematical model of ground-water flow.

Solution Technique

Analytical solutions of the above equation are almost impossible, so various numerical methods must be employed to obtain approximate solutions. The finite-difference method is one such approach wherein the continuous system described by the equation is replaced by a finite set of discrete points in space and time. The partial derivatives are then replaced by differences between functional values at these points. This process leads to systems of simultaneous linear algebraic difference equations; their solution yields values of head at specific points and times. These values constitute an approximation to the time-varying head distribution that would be given by an analytical solution of the partial differential equation of flow. The finite-difference approach to ground-water movement can be accomplished by applying the following steps:

1. A finite-difference grid is superimposed on maps showing the extent of each layer of the multi-layered aquifer or aquifer system, thus for computational purposes, the continuous aquifer is simulated by a set of discrete points for each layer;
2. Pertinent hydraulic and hydrogeologic characteristics of the aquifer are coded for each layer for the appropriate cells within the grid;
3. The governing partial-difference equation is then written in finite-difference form for each of the discrete cells; and
4. a computer is then used to solve numerically the resulting set of linear finite-difference equations for hydraulic head for each of the layers at the center of each node.

For a detailed discussion of the derivation of the finite-difference equation, consult the program documentation and users manual titled <u>A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model</u> (McDonald and Harbaugh, 1984).

Design of the Finite-Difference Grid

To facilitate the input of data, the Carrizo-Wilcox aquifer within the study area was overlain by a grid containing a total of 660 cells. The grid was aligned with the dip and strike of the formations, with 22 rows running more-or-less northeast southwest along strike and 30 columns running generally parallel with the regional dip, southeast-northwest. The rows and the columns are at right angles to each other. Within the outcrop of the Carrizo and Wilcox, and for a short distance on all sides, the cells are square and uniform in size, being two miles on a side with an area of four square miles (2560 acres). From a few miles downdip from the outcrop of the Carrizo, and coastward to a point beyond the downdip limit of usable quality ground water within the Carrizo-Wilcox aquifer, the cells are larger, four by two miles, with an area of eight square miles (5,120 acres). In this area, the columns remain two miles wide, but the rows are four miles wide (see Figure 13). The model has two types of cells, active and inactive. The inactive cells are also called boundary cells. No flow occurs in the inactive cells. Active cells may be of two kinds, either constant or variable head. Throughout layer one, and in the most downdip cells of the other layers, constant-head cells are used to simulate vertical leakage within the system and downdip water-level conditions. The other active cells in layers two through five may simulate either water-table or artesian conditions as the model is placed under various stresses. In the LCRA-TWDB model, there are 518 active cells, but when the overlap of the layers is considered, data must be input for well over a thousand points or nodes.

Boundary Conditions

As far as possible, boundaries of the finite-difference grid of the model were placed along geologic or hydrologic boundaries. The northwest boundary of the model was placed along the updip limit of the outcrop of the Hooper formation of the Wilcox Group. This is a no-flow boundary. The southeast boundary is constant head and was placed along but slightly southeast of the approximate downdip limit of slightly-saline water within the Carrizo aquifer. Input water levels for the last downdip active cells were derived from extrapolation between the closest updip measured water levels for each layer and an arbitrary water level of zero (sea level) assumed for the coast.

The northeast and southwest portions of the model area have no well-defined geologic or hydrologic "boundaries" with which to prescribe boundary conditions. Therefore, the model grid and modeled area were extended to a distance far enough outside of the area of interest, the Colorado River Basin, so as to minimize effects on results of simulations within the interior of the model. This allowed consideration of what was happening within the carrizo-Wilcox aquifer in Bastrop and Fayette Counties without worrying about the effects along the northeast and southwest boundaries of the model. This method is a common one in ground-water modeling. Previous workers have suggested that the model grid should be extended at least three times the aquifer thickness (Franke and others, 1987), and this model grid is well beyond that distance.

Regional Carrizo-Wilcox water-level maps indicate that an

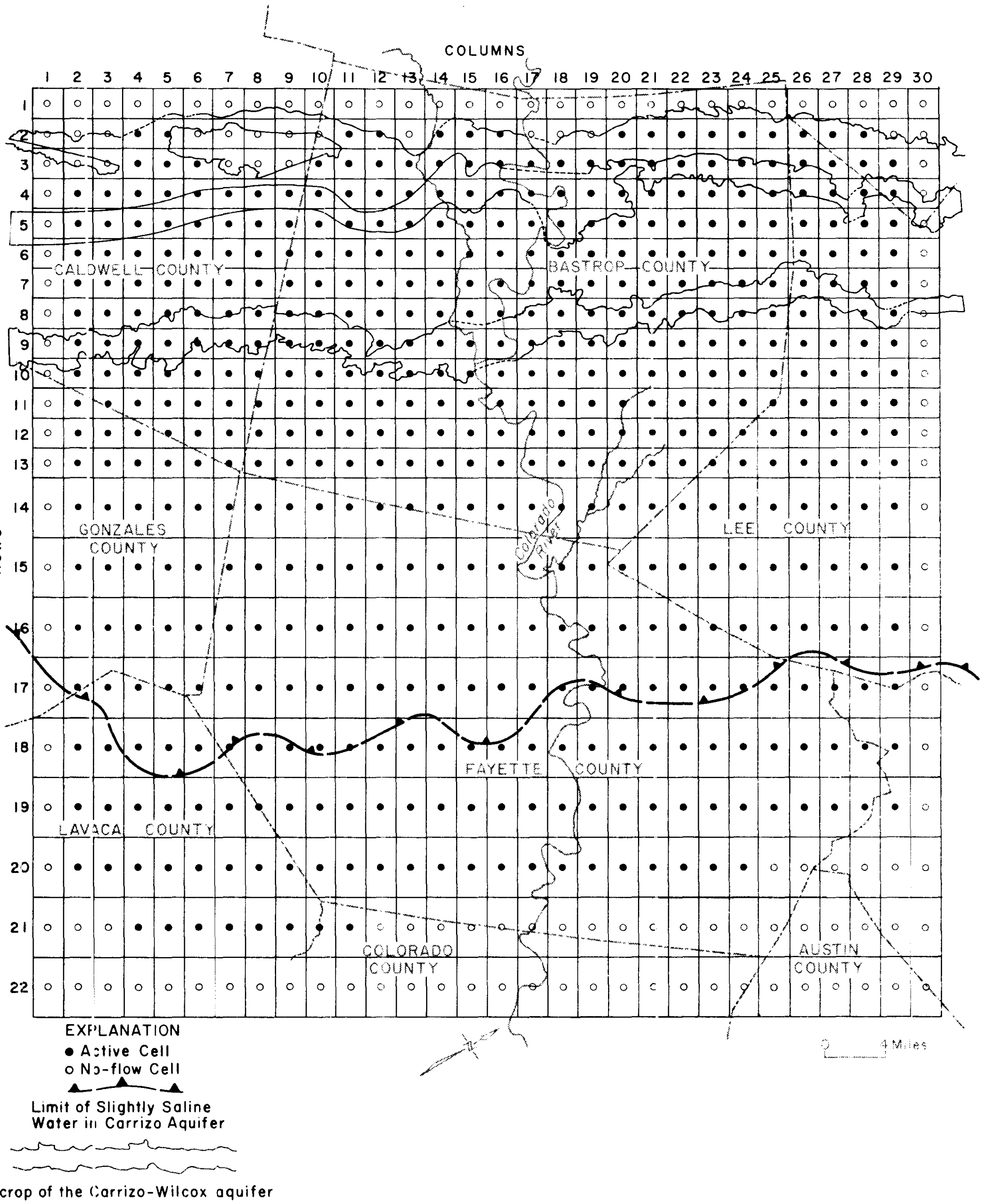

Figure 13

Model Grid

additional "boundary" to ground-water flow within the region is the Colorado River itself. Interpreted directions of ground-water flow, based on water-level contours, are toward the river or parallel to it, but do not cross the river. Model generated heads reflect similar flow patterns and support the existing real data. Model results also show that flow patterns do not change significantly with the addition of projected increases in pumpage. Even though ground-water flow does not cross the Colorado, the river is both a source of water for recharge and a sink for natural discharge of water from the aquifer system. Therefore, model nodes which are crossed by the Colorado River cannot be modeled as no-flow cells. In the Carrizo-Wilcox outcrop, the model's river module is used to represent the river. Where the Carrizo-Wilcox aquifer is under artesian conditions and the Colorado crosses nodes representing the outcrop of the Younger Rocks, cells are assigned water levels that reflect the approximate altitude of the river.

Data Requirements

Input data requirements for the McDonald-Harbaugh Model vary with the problems being simulated. These data are specified by the assignment of a numeric "layer-type code" to each model layer.

In the LCRA-TWDB model, cells in Layer One, which represented the Younger Rocks, were coded with a "1" for layer type 1 which represents strictly unconfined conditions. With this layer assignment, input of the following data were required for each cell of Layer One: specific yield, hydraulic conductivity in the row direction, aquifer bottom elevation, and vertical hydraulic conductivity (Vcont) between this layer and the layer below.

Layers Two, Three, Four, And Five were assigned a "3" for layer-type code 3. This layer designation allows each cell for these layers to be fully convertible between confined and unconfined aquifer conditions. This layer type was used because it allowed the model to realistically handle changes in the transmissivity due to possible changes where water levels might fall below the top of the layer in downdip nodes. This layer type required input of the following data for each cell in each layer: storage coefficient, hydraulic conductivity in the row direction, elevation of the bottom of the aquifer, specific yield, elevation of the top of the aquifer, and vertical hydraulic conductivity between the subject layer and the layer below.

In addition, use of the "well", "drain", and "river" packages required input of other data. The "well" package allows the modeling of both pumpage and recharge. Pumpage data are input into each effected layer and cell. It is given a negative value to indicate the removal of water from the aquifer system. Recharge is input into each layer in each cell on that layer's outcrop and is given a positive value to indicate the addition of water to the aquifer system. Pumpage or water use data were secured from the Board's Water Uses and Projections Unit. Natural recharge was calculated as a percentage of precipitation on the outcrop area.

The "drain" package was used in an attempt to determine the current effective recharge to each of the layers and to the aquifer as a whole. Data requirements for this package were: land surface elevation and the hydraulic conductivity value of the interface between the aquifer and the drain. Use of this package allows an estimation of the amount of rejected recharge from the aquifer and will permit the calculation of a better estimate of recharge from precipitation.

The "river" package allows the modeling of the interaction of the major streams, in this case the Colorado River, with the various layers and gives a better picture of the operation of the aquifer as an entire system. Data input requirements for this package are: the elevation of the stream bed in the cells where it crosses the model, and the hydraulic conductivity of the material of the stream bed.

Procedures and Parameter Estimations, with Ranges

The hydrogeologic data defining the aquifer parameters used in the model were derived from several different sources. The discussions which follow document these sources and the methodologies used to derive the various parameters listed above. Additionally, the ranges for each of these parameters are also given.

Mapping Techniques

The Wilcox Group contains a complex distribution of shale and sand facies which were deposited by ancient river systems (Fisher and McGowen, 1967). Because of this complexity, extreme care was exercised in mapping the individual units of the aquifer. In an attempt to reproduce geohydrologic parameters as nearly correct as possible and to have some agreement with previous work completed by others, the authors utilized much of the work which had been completed by personnel of the Bureau of Economic Geology (Fisher and McGowen, 1967; Henry and Others,1980; and Kaiser, 1974).

Following research of the existing literature, standard correlations for the individual units within the Carrizo-Wilcox aquifer were adopted. These units included, from top to bottom, youngest to oldest, the Carrizo Formation of the Claiborne Group; and the Calvert Bluff, the Simsboro, and the Hooper formations of the Wilcox Group. These subdivisions are well illustrated on a "type log" prepared by Kaiser (1974, p. 20) for use in investigations of lignite in the Wilcox. A total of six geologic cross-sections were constructed for the LCRA-TWDB study (see Figures 5 thru 10). Several of these were reworked from the sections previously constructed for the Board's Central Texas Carrizo-Wilcox Regional Study. All subsequent data determinations, including structural formation "picks" (tops and bottoms, sand and shale thicknesses), and hydraulic conductivity estimates were based on these cross-sections. More than 250 electric logs, including those from both water wells and oil and gas tests, were used to interpret the depositional environments within the Carrizo-Wilcox. These interpretations were based on characteristic patterns on the electric logs which indicated either of two depositional environments, "channel" deposits or "interchannel" deposits. Major developments of fine to coarse sand were considered to have been deposited within "channel" areas. Silty shales, thinly laminated sands, and shales were considered to have been deposited in "interchannel" areas. In this study, both the net sand and the net shale intervals were considered.

Initially, weighted average permeabilities were determined for each of the units. These averages were based on the assignment of estimated permeabilities to each individual sand, silt, and shale bed within each unit on each electric log considered. These assignments were based on the environment of deposition, "channel" or "interchannel" and followed the usage of Henry and others (1980, p. 3). A value of 1 gallon per day per foot per foot (gpdpfpf) was assigned to shales and silty shales. Sands associated with the "interchannel" areas were assigned a value of 25 to 50 gpdpfpf, while those in the "channel" areas were given values between 150 and 500 gpdpfpf. In general, the values were kept in the middle of these ranges in an effort to keep the model conservative. Contour maps were then constructed showing the "weighted average permeability" for each layer. These maps are included as Figures 8, 9, 10, and 11 in Appendix 5.

Structural Data

Operation of the model required the input of data on the elevation of both the top and base of each of the layers. These data were determined from electric logs of both water wells and oil and gas tests, and used to make structural maps showing the tops of the Carrizo Sand (which is also the base of the Younger Rocks)(Figure 3, Appendix 5), the Calvert Bluff formation (Figure 4, Appendix 5), the Simsboro formation (Figure 5, Appendix 5), and the Hooper formation (Figure 6, Appendix 5). An additional map was constructed showing the base of the Hooper formation, which is also the top of the Midway Group and the base of the Carrizo-Wilcox aquifer (Figure 7, Appendix 5). The elevation of the ground surface at each node was also determined from topographic maps. The grid system map showing the cells for the model was overlaid on each of the resulting maps and data for each cell node was determined for each appropriate layer. The resulting data file was input into the model.

Transmissivities and Hydraulic Conductivities

Using the grid map and the maps previously constructed showing the "weighted average permeabilities" of the various formations (Figures 8 through 11, Appendix 5), data on the hydraulic characteristics of the layers were input to the model. The type of information which was required for each layer varied according to the "code" assigned to the individual cells. Cells with code "1" for strictly water table conditions required input of a figure for hydraulic conductivity in the row direction (in feet per second). The model used this figure along with water level and the elevation of the base of the layer to calculate transmissivities for each node with this code. All cells in Layer one (Younger Rocks) were coded "1". The active cells in layers two through five were coded "3", which indicates that the cell is fully convertible between confined and unconfined conditions. Data input required for this type of cell includes storage coefficient (only for transient simulations), hydraulic conductivity in the row direction (in feet per second), elevation of the bottom of the layer, specific yield (only for transient simulations), elevation of the top of the layer, and the Vcont between this layer and the layer below. Vcont is actually a characteristic of two layers, it is included as part of layer data for programing convenience and ease of input. Since it represents an interrelationship between one layer and the layer below, no Vcont is entered for the bottom layer of the model.

In the model, the horizontal hydraulic conductivity (which is used to calculate transmissivity) specified for the row direction in each cell is multiplied by a horizontal anisotrophy factor to calculate hydraulic conductivity in the column direction. One value for the horizontal anisotrophy factor is specified by the user for each layer in the model. In the LCRA-TWDB model, a factor of "1.0" was applied to all five layers. Thus, the horizontal conductivity and transmissivity for each cell were the same in both the row and column directions for all layers.

Simulations

Calibration and Stress Scenarios

Simulations using the Carrizo-Wilcox model were run in three phases. Phase one runs were designed to determine the model's response to changes in horizontal hydraulic conductivity, vertical hydraulic conductivity, and model calculated leakage factors. Phase two runs were similar to those in phase one, but also incorporated the model's drain and river packages. Phase three runs tested the aquifer's response to differential rainfall conditions and projected future pumpage scenarios.

All first phase simulations were made under steady-state conditions. This approach was taken because, under present conditions, the Carrizo-Wilcox appears to be in a state of dynamic equilibrium within the study area. Regionally, the system is not heavily developed; static water levels are generally high; and water levels have shown no significant fluctuations with time.

An important goal of most ground-water modeling studies is to design and calibrate the model so that computed heads match actual heads measured in the field. This presents a problem in many instances because of a lack of well data adequately dispersed throughout the modeled area. This is especially true of the LCRA-TWDB model because of the limited number of wells which penetrate to the Carrizo-Wilcox aquifer in its downdip extent. Within this area, which has a relatively limited population, adequate water for domestic and livestock supply can usually be derived from shallower aquifers (Younger Rocks). The few available deeper wells are completed in the Carrizo Sand. There is little or no data available on the lower parts of the Carrizo-Wilcox aquifer, especially head data. Figure 14 shows the study area with the locations of water wells completed in the Carrizo-Wilcox aquifer from which reliable head data was obtained and used in this model study.

Regional distribution of the available Carrizo-Wilcox head data in central and east Texas does not indicate large differences between heads in the Carrizo Sand and those in the Wilcox Group (Fogg and Kreitler, 1982, and Thorkildsen and Price, in press). Therefore, measured Carrizo heads were used to compare with model generated heads in the study area. Adjustments were made to the ratio between vertical and horizontal hydraulic conductivity until computed heads for Layer two (Carrizo Sand) duplicated measured Carrizo heads with reasonable accuracy (Figure 15). Computed heads of Layers three. four, and five did not vary significantly from those of Layer two.

Phase one simulations incorporated 1985 pumpage figures for major users (estimated from the 1985 Water Use Inventory prepared by the Board). Recharge to the Carrizo-Wilcox outcrop area was simulated by inputting constant heads for the water table nodes in Layers two through five. These heads were based on measured heads in wells in the outcrop area (Figure 2, Appendix 5). Holding heads in the outcrop constant insured that an adequate amount of water would be available for transmission both to discharge areas in the outcrop and downdip without causing water-level fluctuations in the outcrop area. Heads were also held constant in Layer one (Younger Rocks) for the entire model grid in order to provide adequate water for possible leakage between the Younger Rocks and the Carrizo-Wilcox.

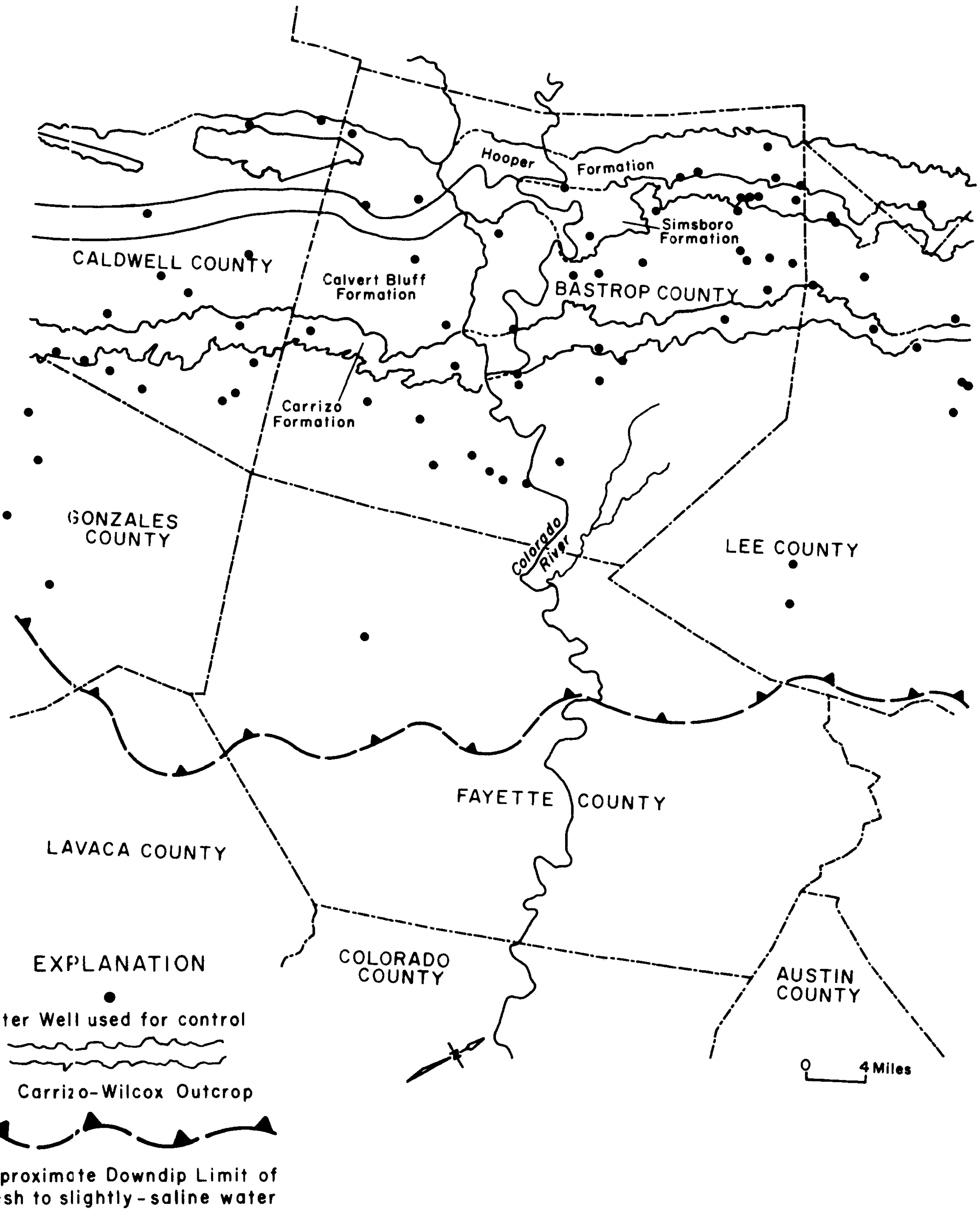

Figure 14
Study Area with Location of Water Wells Used for Control

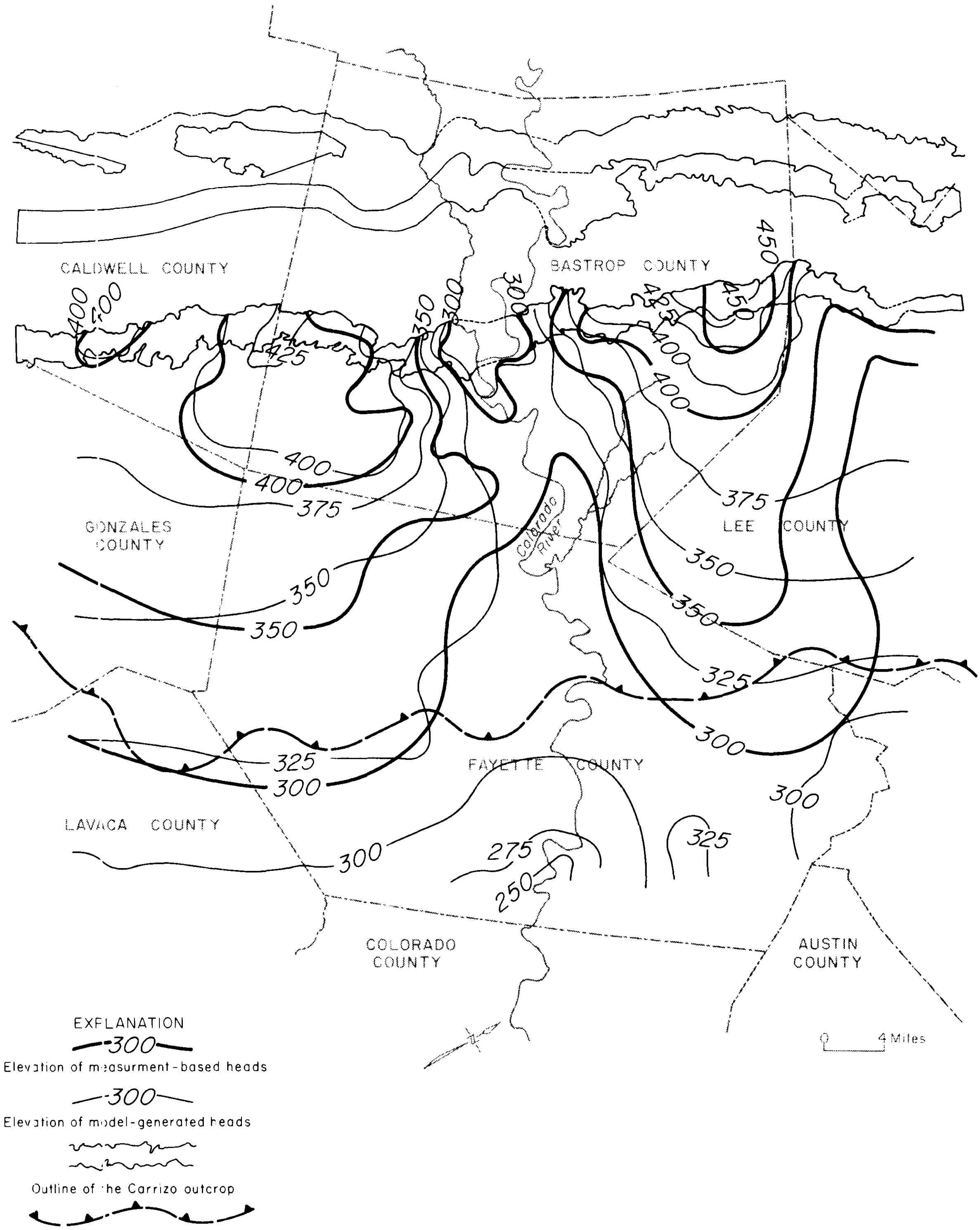

Figure 15

Measured and Model Generated Heads in Layer 2

Phase two simulations (runs 2-A through 2-G) were also run under steady-state conditions. The ratio of vertical to horizontal hydraulic conductivity which had produced the best reproduction of measured Carrizo heads in phase one was maintained in all phase two simulations. Also, the final computed heads for all layers derived in phase one were used as starting heads for phase two runs. This was done in order to minimize initial head fluctuations and to aid the model in arriving at a final solution in as short a time as possible. The main difference between phase one and phase two simulations was that in phase two constant heads were removed from the outcrop area nodes for Layers two through five (Carrizo-Wilcox) and the model's drain and river modules were incorporated.

To provide recharge to the outcrop area in phase two, with the absence of constant heads, the model's well module was used. Recharge was simply input as negative pumpage. Each outcrop node in Layers two, three, four, and five was assigned recharge value equal to 15 percent of the mean annual rainfall.

The drain module was incorporated to try and simulate both effective and rejected recharge in the outcrop area. If the Carrizo-Wilcox aquifer system is currently full, a significant portion of the total recharge that enters the aquifer is probably expelled within the outcrop area through evaporation and losses to springs, seeps, and streams in areas of relatively low elevation. The drain module was meant to represent small streams, seeps, and other natural features by which recharge is rejected in the outcrop. Elevations of the drains were set equal to the elevation of the land surface at each node location. In addition, each drain was assigned a conductance term of one square foot per second. This is meant to represent the flow relationship between the drain material and the aquifer. A blanket value was used for this term because the drain module was utilized in an attempt to simulate natural features as opposed to man-made drainage structures. Using these parameters, the model calculated flow values for each node in which the final simulated water level was above the drain elevation. For drain nodes where the final water levels were lower than the drain elevation, no flow calculation was made. All flows were then totaled and a cumulative amount representing total flow out of the system was obtained. With this value and that for the original recharge input, the amount of effective recharge (that which remained within the aquifer, moving downdip, and available for pumpage) was estimated for various aquifer and climatic conditions.

While no inflow-outflow studies are known which cover the Carrizo-Wilcox reach, water-table maps indicate that a significant component of ground-water flow in the Carrizo-Wilcox within the study area is toward the Colorado River. The model's river module was used in an attempt to simulate this relationship. The river module operates in a manner similar to the drain module. Grid nodes through which the Colorado River flow were designated "river" nodes and assigned parameters which included: (1) elevation of the river stage; (2) elevation of the river bed; and (3) hydraulic conductance of the river bed material. "River" nodes with computed water levels above the river bed elevation at the end of a simulation period indicated a flow from the aquifer to the river for that period. Those with water levels below the river bed elevation showed flow from the river to the aquifer.

An additional goal of phase two simulations was to determine the effect of large increases in pumpage from the aquifer on effective recharge to the Carrizo-Wilcox. To accomplish this, added hypothetical pumpage was taken from the aquifer along a line of nodes reaching across the entire grid. This line was located parallel to the outcrop but approximately halfway between the center of the outcrop and the downdip limit of slightly-saline water. The majority of the increased pumpage was taken from the Carrizo Sand and the Simsboro Formation, with lesser amounts from the Calvert Bluff and Hooper Formations. The total amounts of pumpage were arbitrary, but the relative amounts derived from each layer were designed to reflect scenarios which might be expected if such pumpage were actually to take place. The following tabulation illustrates the amounts of pumpage from each layer expressed as a percentage of the mean annual rainfall.

PHASE TWO PUMPAGE
(PERCENT OF MEAN ANNUAL RAINFALL)

LAYER	RUN-2D	RUN-2E	RUN-2F	RUN-2G
Carrizo	0	15	25	50
Calvert Bluff	5	5	5	10
Simsboro	10	15	25	50
Hooper	1	1	1	1

In phase three, two long-term transient simulations were made (runs 3-A and 3-B). They incorporated (1) average rainfall conditions in conjunction with relatively high pumpage based on "future high demands" from the State Water Plan (Texas Department of Water Resources, 1985) applied from 1985 through the year 2029; and (2) a combination of yearly measured rainfall data for the years 1947-1961, which included an extended drought period, applied in conjunction with pumpage based on the "projected high case demands" for the year 2029 again from the State Water Plan.

Results

The best results for phase one simulations were obtained when the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity was between 0.001 and 0.0001 over the majority of the modeled area, including all of layer one (Younger Rocks). In a narrow strip along the course of the Colorado River, layers two through five (The Carrizo-Wilcox Aquifer) were assigned vertical and horizontal hydraulic conductivities with ratios between 0.01 and 0.001. These ratios are similar to those used by the Bureau of Economic Geology in a modeling study of the Carrizo-Wilcox in the Oakwood Salt Dome area of east Texas (Fogg and others, 1983). The Model generated heads using these values of hydraulic conductivity most closely matched actual measured values of head. Differences between generated and measured heads at measured locations ranged from two to 33 feet. The average difference was 15 feet. Figure 15 shows the relationship between measured and model generated heads for the Carrizo Sand in the study area.

Results of the initial simulations in phase two (runs 2-A and 2-C) indicate that, under average rainfall conditions and with 1985 pumpage, annual effective recharge to the Carrizo-Wilcox outcrop area is between three and four percent of the mean annual rainfall, or about 33,000 acre-feet. The simulations show that total recharge is about 144,000 acre-feet. Of the rest of that total about 65,000 acre-feet is rejected through natural discharge in the outcrop area through seeps and springs, and about 45,000 acre-feet flows to the Colorado River in the outcrop. In addition, pumpage within the outcrop totals about 1,000 acre-feet. Results from these simulations also show discharge from the Carrizo-Wilcox to the overlying Younger Rocks in the form of interformational leakage. In Bastrop and northern Fayette Counties, this flow is approximately 9,000 acre-feet per year. The results of these initial simulations illustrate and support the concept that the Carrizo-Wilcox aquifer is essentially a full system and accepts only a relatively small portion of the available recharge.

Four additional phase two simulations were run which employed hypothetical high pumpage along a line between the center of the Carrizo-Wilcox outcrop and the downdip limit of slightly-saline water (runs 2-D thru 2-G). The purpose of these simulations was to determine the impact of additional pumpage on effective recharge to the aquifer. Pumpage was assigned using the model's well module. At each node along the pumpage line, and for Layers two through five for each node, pumpage values equal to a percentage of the mean annual rainfall was assigned. The percentage varied, increasing with each successive run (see Simulations Section above).

The results of these simulations is summarized below.

SUMMARY OF PHASE II SIMULATIONS FOR
BASTROP AND FAYETTE COUNTIES
(in acre-feet per year)

RUN	PUMPAGE*	EFFECTIVE RECHARGE OUTCROP	EFFECTIVE RECHARGE ARTESIAN#	REJECTED OUTCROP RECHARGE	DISCHARGE TO THE COLORADO RIVER	LATERAL OR DOWNDIP FLOWa
2-C	1,000	33,000	-9,000	65,000	45,000	-24,000
2-D	50,000	42,000	+31,000	58,000	43,000	-14,000
2-E	75,000	44,000	+42,000	57,000	42,000	-12,000
2-F	106,000	45,000	+64,000	57,000	41,000	-4,000
2-G	208,000	58,000	+136,000	49,000	36,000	+13,000

All runs received an input recharge of 144,000 acre-feet, which is equal to 15 percent of the mean annual rainfall on the outcrop of the Carrizo-Wilcox in Bastrop and Fayette Counties (total rainfall equals 964,630 acre-feet).

* This column is the total of water-table pumpage from the Carrizo-Wilcox plus hypothetical downdip pumpage from Bastrop County. Water-table pumpage is included because it was already included as part of the recharge terms.

\# Vertical flow into (+) or out of (-) the Carrizo-Wilcox aquifer within the artesian zone in Bastrop and Fayette Counties.

a Horizontal flow entering (+) or leaving (-) the area of the Carrizo-Wilcox containing fresh-to-slightly saline water in Bastrop and Fayette Counties.

In addition to effective recharge increasing significantly in these simulations, discharge to the Colorado River correspondingly decreased incrementally with each increase in pumpage. This produced a total decrease of about 20 percent, from 45,000 acre-feet per year in run 2-D to 36,000 acre-feet per year in run 2-G. As expected, the imposition of such large amounts of additional pumpage on the system created large cones of depression in the water table. These areas of water level decline were generally aligned along the line of pumpage. The greatest declines were associated with the Carrizo Sand (Layer 2) and the Simsboro Formation (Layer 4). In all simulations, the largest amounts of pumpage were taken from these two layers. Maximum water level declines as a result of these high pumpage scenarios ranged from more than 50 feet in run 2-D to over 200 feet in run 2-G. These maximum declines occurred on the southwest and north east margins of the model within the areas added to the model to minimize the possible boundary effects. Within Bastrop and Fayette Counties maximum declines ranged from just over 40 feet in run 2-D to almost 160 feet in run 2-G. Figures 16, 17, 18, and 19 illustrate the location, extent, and range of water-level decline for the Carrizo Sand and Simsboro Formation in runs 2-D and 2-G.

In addition to increasing effective recharge in the outcrop area, the large water-level declines associated with the heavy

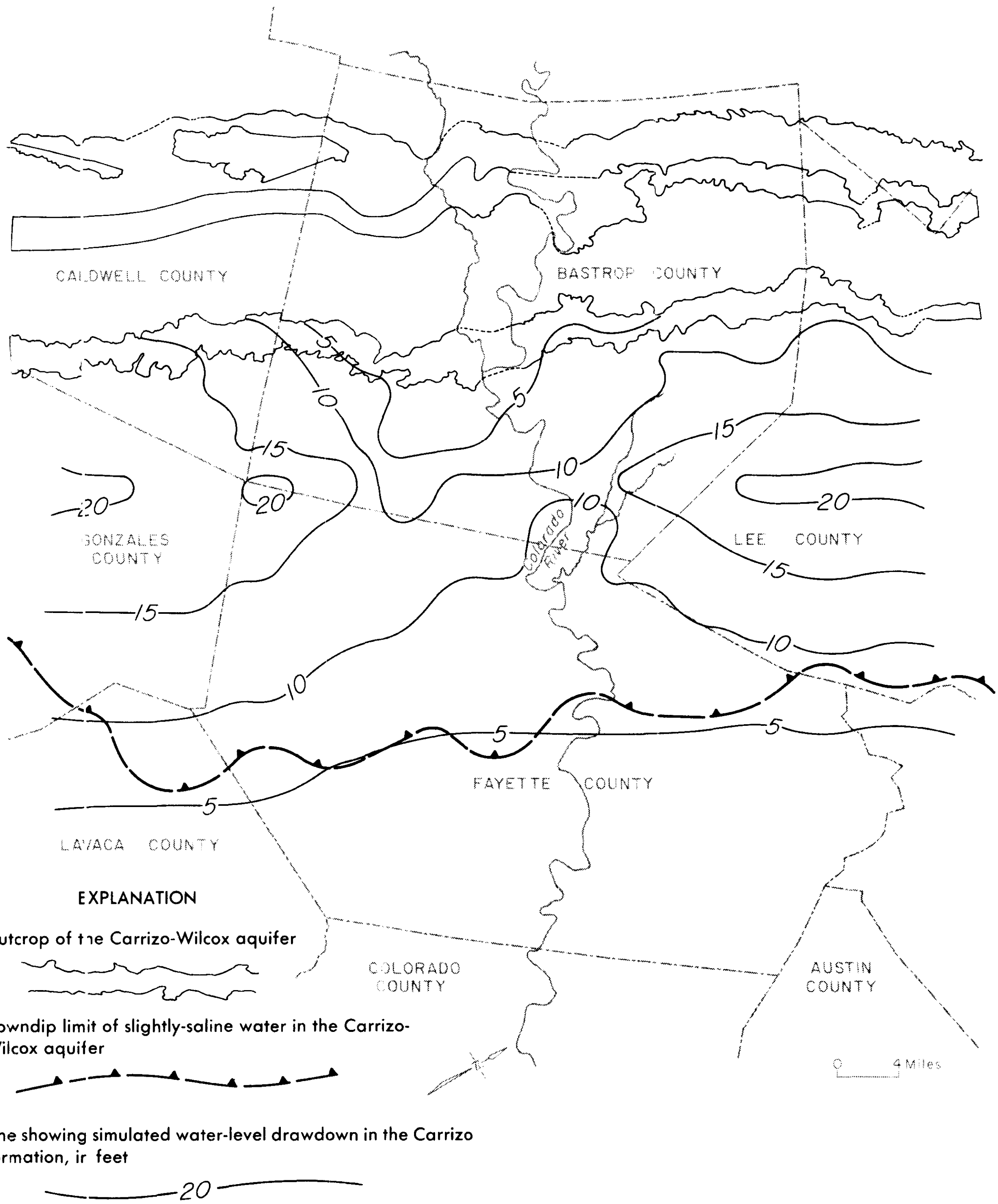

Figure 16
Simulated Water-Level Drawdowns in the Carrizo Formation, Run 2-D

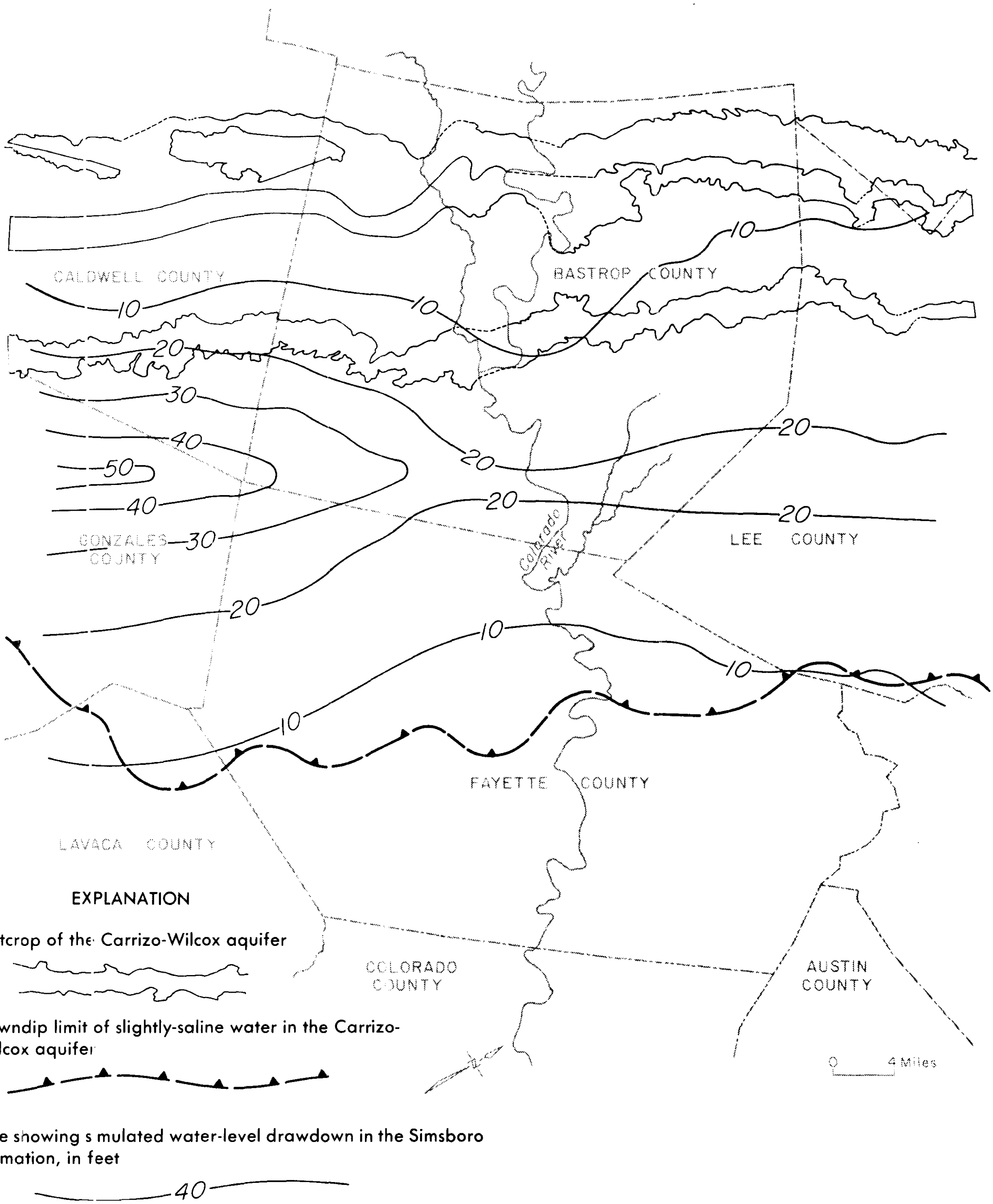

Figure 17

Simulated Water-Level Drawdowns in the Simsboro Formation, Run 2-D

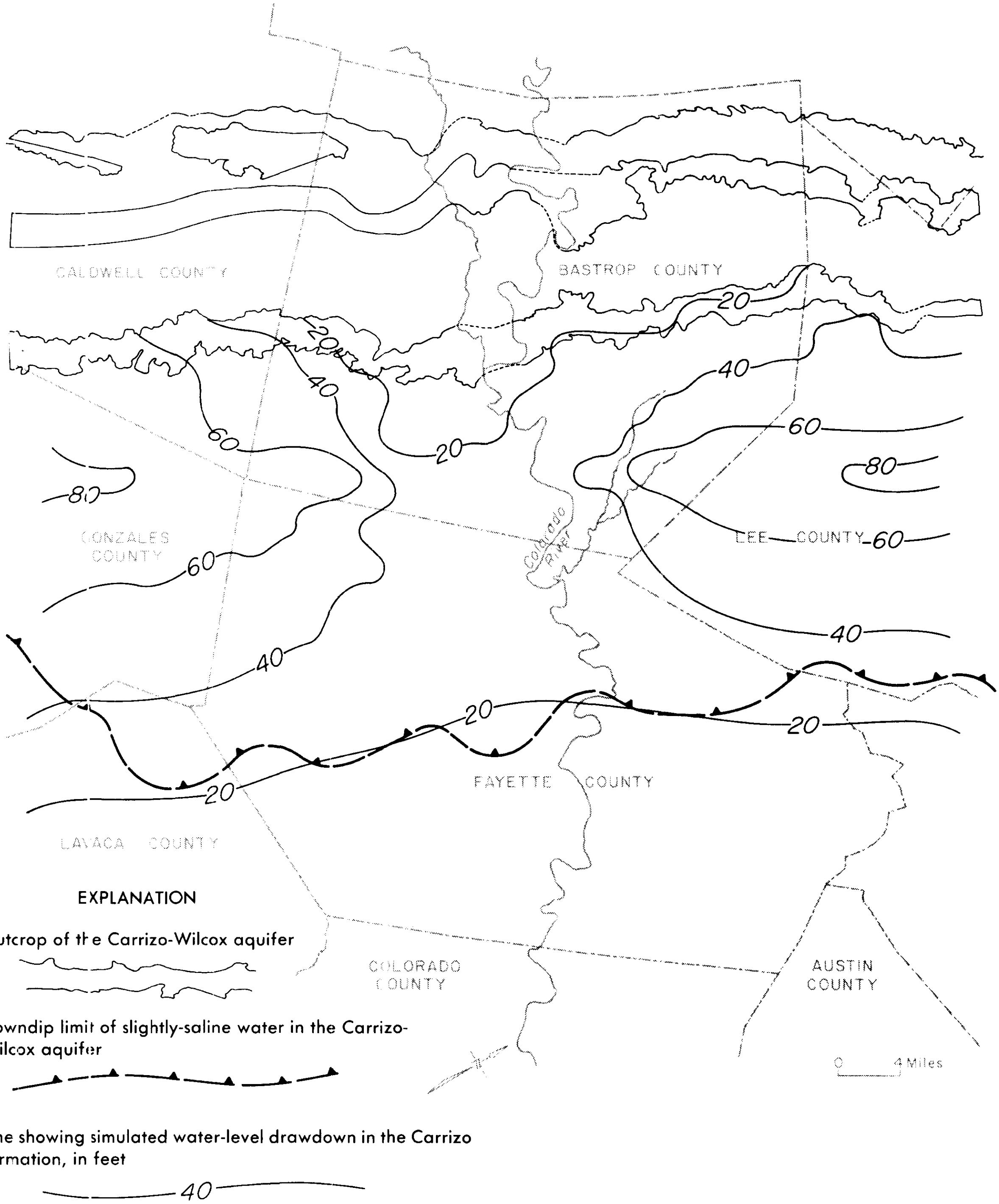

Figure 18

Simulated Water-Level Drawdowns in the Carrizo Formation, Run 2-G

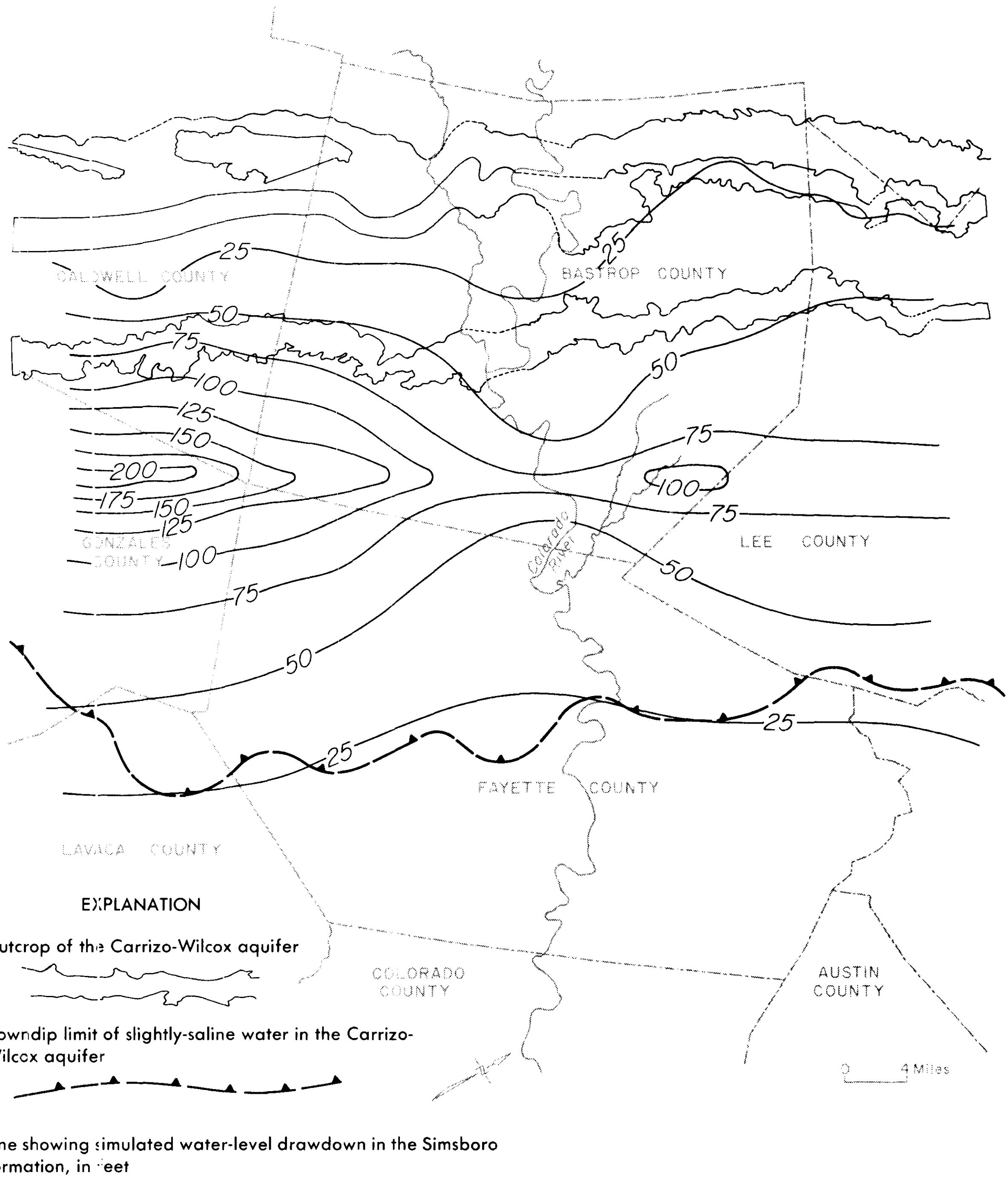

Figure 19

Simulated Water-Level Drawdowns in the Simsboro Formation, Run 2-G

pumpage imposed in runs 2-D through 2-G also created a large vertical gradients between the Carrizo Sand and the Younger Rocks to reverse the interformational flow, formerly about 9,000 acre-feet from the Carrizo to the Younger Rocks, inducing significant amounts of downward flow, from the Younger Rocks to the Carrizo. The results of run 2-G indicate that as much as 136,000 acre-feet of water per year could enter the Carrizo-Wilcox from this source. At first, this amount may seem unrealistically high. If the total area effected is considered, however, only a few gallons per square foot per year is needed to produce the total. Because of the presence of relatively poor quality water in at least some portions of the Younger Rocks, this change in the direction of interformational leakage may not have a desirable effect on the Carrizo-Wilcox aquifer. Without additional data and a much more detailed model, it is impossible to accurately predict its effect.

Phase three consisted of transient simulations designed to show the aquifer's response to variations in pumpage and precipitation over a long period of time. The first simulation (3-A) incorporated average rainfall data and systematically increasing pumpage over a 45 year period from 1985 to 2029. Modeled pumpage amounts from the Carrizo-Wilcox aquifer in Bastrop County ranged from 5,763 acre-feet in 1985 to 14,479 acre-feet in 2029. The 1985 pumpage represented actual reported and/or estimated pumpage, while the values for increased future pumpage were based on "future high case demands" from the State Water Plan (Texas Department of Water Resources, 1985). The pumpage, both present known and future projected was distributed throughout the model grid to reflect the actual locations of known well fields belonging to the major users of Carrizo-Wilcox water within the study area. Well data for the different fields was used to determine which model layers would be pumped. Results of run 3-A indicate no significant water-level changes within the Bastrop and Fayette Counties. The largest drawdowns, associated with pumping centers, occurred on the Simsboro Formation outcrop area, but did not exceed 17 feet even with maximum pumpage. Figure 20 shows the maximum drawdown for each layer of the Carrizo-Wilcox aquifer (Layers 2 through 5) for the entire 45 year simulation.

Effective recharge in the outcrop area remained at between three and four percent of the mean annual rainfall although the actual amount did increase slightly from about 33,000 acre-feet in 1985 to just less that 35,000 acre-feet in 2029. In response to the increased pumpage, interformational leakage from the Carrizo Sand (Layer 2) to the Younger Rocks (Layer 1) decreased from 9,000 acre-feet per year to 6,500 acre-feet per year during the same 45 year period. Flow to the Colorado River also decreased slightly, from about 45,000 acre-feet in 1985 to slightly less than 44,000 acre-feet in 2029. While these are the kinds of changes in flow within the Carrizo aquifer system that would be expected with increases in pumpage, none

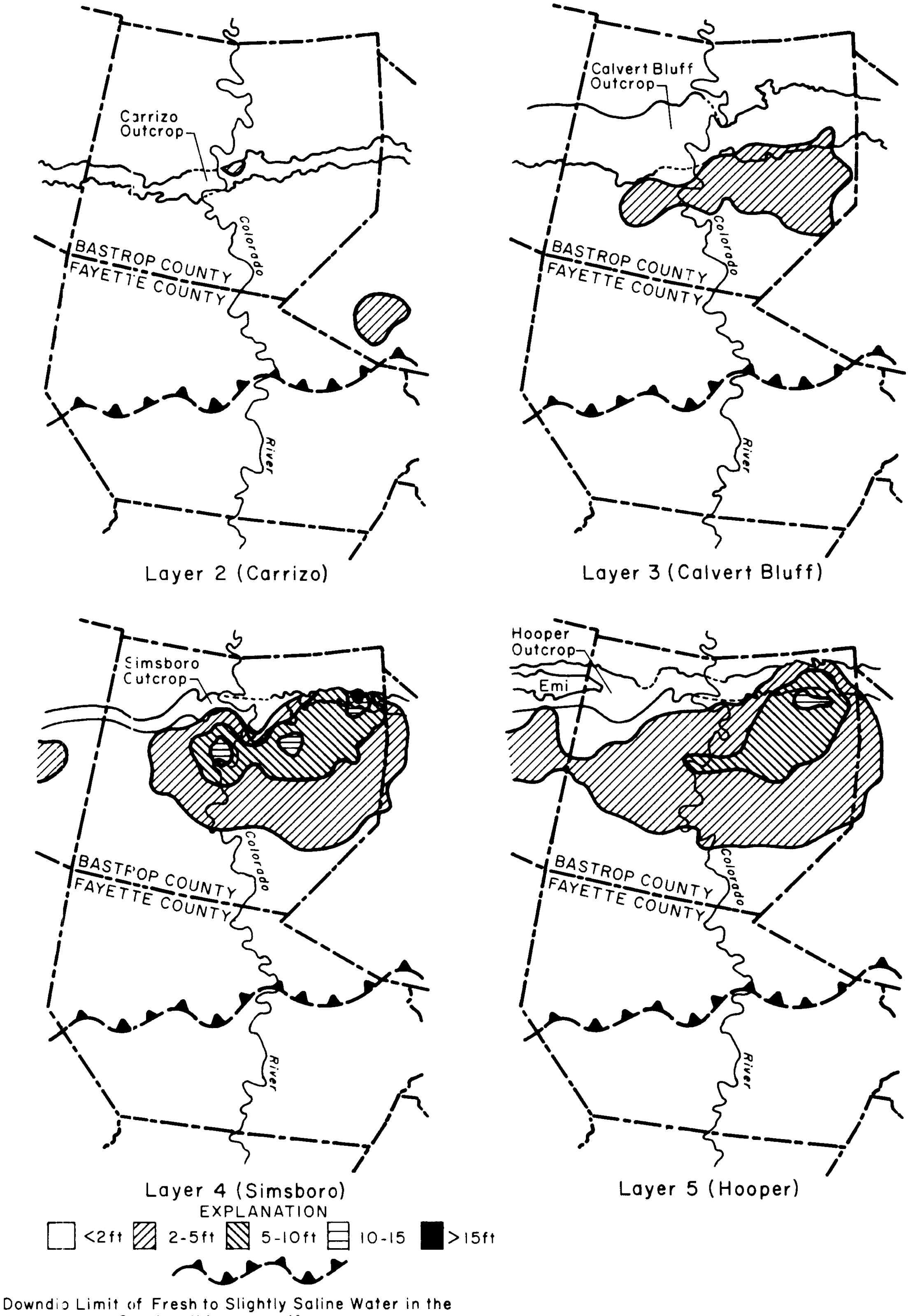

Figure 20
Maximum Drawdowns, Run 3-A

of the magnitudes represent a significant deviation from the initial aquifer conditions.

One additional phase three simulation was made using a combination of measured rainfall data from the years 1947 - 1961 applied in conjunction with pumpage based on the "projected high case demands" for the year 2029 from the State Water Plan (run 3-B). This simulation was intended to test, within Bastrop and Fayette Counties, the aquifer's response to an extended period of low rainfall (drought) in conjunction with the highest projected future pumpage. To further stress the system, the amount of rainfall allowed to enter the aquifer as total recharge within the outcrop was reduced from 15 to 10 percent of the total yearly rainfall. Yearly total recharge during this simulation ranged from 42,000 acre-feet for the driest year to 144,000 acre-feet for the wettest year.

Water-level declines in response to decreased rainfall and increased pumpage reached a maximum of 13 feet at the end of the first year. Once again, the Simsboro Formation experienced the greatest modeled declines due to the largest amounts of pumpage coming from this layer. With subsequent stress periods (years), the water levels fluctuated in direct response to the amount of rainfall, since pumpage remained constant. Magnitudes of fluctuation were very small, and rises or declines did not vary by more than a foot over any one year. The largest simulated declines, associated with periods of lowest rainfall, were 15 feet in the simsboro Formation. During periods with relatively large amounts of rainfall following drier periods, water-level recoveries also occurred.

Since the final simulated water levels for each yearly stress period controlled the magnitude and direction of the horizontal and vertical flow within the model, the amount of total and effective recharge, discharge to the Colorado River, and interformational leakage all varied as water levels changed in response to changes in applied rainfall. When rainfall was high, the resulting heads would rise causing rejected recharge and flow to the Colorado River within the outcrop to increase. The opposite was true when simulated rainfall (and resulting total recharge) was low. Total flow as rejected recharge and flow to the Colorado River represent a significant amount of water leaving the aquifer outcrop area which is lost from the aquifer system. In run 3-B, the total amount of water lost to these outflows ranged from approximately 48,000 acre-feet during the time of lowest rainfall to about 74,000 acre-feet during the time of highest rainfall.

With the exception of the two stress periods which simulated the lowest rainfall conditions, results of run 3-B indicate that effective recharge to the Carrizo-Wilcox aquifer in Bastrop County ranged from less than one to about five percent of the annual rainfall or from about 2,000 acre-feet to nearly 69,000 acre-feet. This large range of values is due to the large variance in the amount of rainfall. Since, as mentioned above, water levels and, therefore, loss of water as rejected recharge and underflow to the Colorado River within the outcrop area, did not change as drastically as did rainfall from one stress period to another, at least on a percentage basis; the rejected recharge and discharge to the Colorado River become larger percentages of the total input recharge as rainfall decreases. In turn, the amount of effective recharge decreases. To illustrate this point to an extreme, consider the two stress periods simulating the lowest rainfall years. In these two years, rainfall and subsequent recharge were lowest for the entire simulation. The simulated water levels were also at their lowest. Therefore, rejected outcrop recharge and discharge to the Colorado River were smaller than for periods of higher rainfall (with resulting higher water levels). While the amount of rainfall was significantly smaller when compared with the preceding year, the resulting water levels did not drop significantly (less than one foot). So even though outflow within the outcrop, in the form of rejected recharge and discharge to the Colorado River, was lower than the previous stress period, total recharge was even much lower by comparison, since it is directly tied to the rainfall. As a result, the combined total of rejected recharge and discharge to the Colorado River exceeded the total recharge (ten percent of the rainfall). This situation occurred only twice during run 3-B, and these two cases were isolated between periods of relatively higher rainfall. If such extremely low amounts of rainfall and therefore, recharge, were to persist over a period of several consecutive years, the model results indicate that heads would continue to fall and recharge rejected in the outcrop would decline.

The results of simulation 3-B show an additional source of effective recharge to the Carrizo-Wilcox under the imposed conditions, in the form of interformational leakage from the overlying Younger Rocks (Layer 1). Amounts varied in response to head changes in the artesian portion of the Carrizo-Wilcox aquifer system. Leakage totals within Bastrop and Fayette Counties ranged from 500 acre-feet during the initial year of the simulation, to a maximum of about 2,800 acre-feet for the year of lowest rainfall. Although this increase is significant when compared to present pumpage, it is still very small when compared to the total availability of water from the entire study area. As mentioned above, little is known as to the effects on water quality within the upper portion of the aquifer system that might result from such interformational leakage.

Based on model generated water levels and aquifer parameters such as sand thickness, coefficient of storage, and geologic structure, a estimate was made of the total volume of fresh-to-slightly saline water in artesian storage and within saturated sands of the Carrizo-Wilcox aquifer in the study area.

In Bastrop and Fayette Counties, the total fresh-to-slightly saline water in artesian storage is approximately 560,000 acre-feet. Of this total, it is estimated that 104,000 acre-feet is recoverable without causing encroachment of more saline water from downdip portions of the aquifer. This figure is based only on the instantaneous amount of water in storage and ignores recharge and interformational leakage from the overlying strata.

The saturated sands of the Carrizo-Wilcox contain a substantial volume of ground water. Assuming total saturation within the artesian portion of the aquifer and partial saturation within the water-table portion of the aquifer, the volume of fresh-to-slightly saline water within the sands of the Carrizo-Wilcox aquifer in Bastrop and Fayette Counties is approximately 217,000,000 acre-feet. Because of the great depth of most of this water and the complicated nature of the aquifer, it is difficult if not impossible to accurately determine the amount that would be recoverable. Such an evaluation would need to consider not only aquifer parameters and the effects of dewatering and updip migration of poorer quality water, but the complicated economics of well and well-field location and construction as well as pumping lifts.

Limitations

The primary goal of constructing a ground-water flow model of the Carrizo-Wilcox aquifer within the study area was to develope a tool which could be used effectively for ground-water evaluation and management within the jurisdictional area of the Lower Colorado River Authority. When making applications of the model, it is important to realize that there are limitations inherent to this, or any, model which must be considered.

Geologic and hydrologic parameters used in the model are reasonable and were determined using consistent and documented methods. Improvements in model accuracy can always be achieved with additional data, however. More water-level data, especially for the lower layers of the system, would be a most valuable addition to the data base. More detailed information on horizontal and vertical flow and their interrelationship, would also improve results. Representing non-homogeneous layered sediments with weighted average hydraulic conductivities will always be a limitation in any ground-water model of a real-world flow system.

Another uncertainty within the modeled area is the effect of faulting on flow patterns within the Carrizo-Wilcox aquifer. Water-level maps do not indicate any significant regional variations which might be due to faulting, although undoubtedly, some local flows are affected. Modeling this particular aspect of this aquifer would require a much more site-specific approach with a much smaller grid spacing and more detailed water-level data.

This project is regional in nature and the model was designed accordingly. It is not, nor is any ground-water model, a final "stand alone" solution for all ground-water questions concerning the Carrizo-Wilcox aquifer. However, in conjunction with sound geologic and hydrologic techniques the model developed here can be a useful tool; in formulating and evaluating sound management decisions, especially about conjunctive use of surface and ground water. As more information about the aquifer becomes available and model accuracy is improved, hopefully the limitations outlined can be minimized.

BIBLIOGRAPHY OR SELECTED REFERENCES

Bammel, B.H., 1979, Stratigraphy of the Simsboro formation, east-central Texas: Baylor Geological Studies Bull. 37, 40 pp.

Barnes, V.E., 1970, Waco Sheet, The Geological Atlas of Texas: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

______, 1974, Austin Sheet, The Geological Atlas of Texas: The University of Texas at Austin, Bureau of Economic Geology, scale: 1:250,000.

Carr, J.T., Jr., 1967, The Climate and Physiography of Texas: Texas Water Devel. Board Rept. 53, 27 pp.

Dallas Morning News, 1981, Texas almanac and state industrial guide, 1982-1983: A.H. Belo Corp., pp.

Ferris, J.G., Peckham, R.C., Peters, H.J., Richter, R.C., Weber, E., 1968, Ground-Water Short Course Manual: Texas Water Development Board, 468 pp.

Fetter, C.W., Jr., 1980, Applied Hydrogeology: Columbus, Merrill Publishing Company, 488 pp.

Fisher, W.L., 1964, Sedimentary patterns in Eocene cyclic deposits, northern Gulf Coast region: Kansas Geological Survey Bull. 169, v.1, p.151-170.

______, and McGowen, J.H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to the occurrence of oil and gas: Gulf Coast Assoc. of Geological Societies' Transactions, v.17, p.105-125.

Fogg, G.E., Kaiser, W.R., Ambrose, M.L., and MacPherson, G.L., 1983, Regional aquifer characterization for deep-basin lignite mining, Sabine Uplift area, northeast Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circ. 83-3, 30 pp.

Fogg, G.E., Seni, S.J., and Kreitler, C.W., 1983, Three - dimensional ground-water modeling in depositional systems, Wilcox Group, Oakwood Salt Dome area, east Texas: The University of Texas at Austin, Bureau of Economic Geology Rept. of Investigations No. 133, 55 pp.

Fogg, G.E., and Kreitler, C.W., 1982, Ground-water hydraulics and hydrochemical facies in Eocene aquifers of the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology Rept. of Investigations No. 127, 75 pp.

Follett, C.R., 1966, Ground-water resources of Caldwell County, Texas: Texas Water Devel. Board Rept. 12, 141 pp.

______, 1970, Ground-water resources of Bastrop County, Texas: Texas Water Devel. Board Rept. 109, 138 pp.

Franke, and others, 1987, Definition of Boundary and Initial Conditions in the Analysis of Saturated Ground-Water Flow Systems--an Introduction, Tech. Water-Resources Inv., Bk. 3, Chap. B5: U. S. Geological Survey, 15 pp.

Freeze, R.A., and Witherspoon, P.A., 1967, Theoretical analysis of regional ground-water flow, Effect of water-table configuration and subsurface permeability variation: Water Resources Research, v. 3, no. 2, pp. 623-634.

Guyton, W.F., and Associates, 1972, Ground-Water conditions in Anderson, Cherokee, Freestone, and Henderson Counties, Texas: Texas Water Devel. Board Rept. 150, 250 pp.

Henry, C.D., Basciano, J.M., and Deux, T.W., 1980, Hydrology and water quality of the Eocene Wilcox Group, significance for lignite development in east Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circ. 80-3, 9 pp.

Kaiser, W.R., 1974, Texas lignite, near-surface and deep-basin resources: The University of Texas at Austin, Bureau of Economic Geology Rept. of Investigations No. 79, 70 pp.

______, 1976, Calvert Bluff (Wilcox Group) sedimentation and the occurrence of lignite, in Kaiser, W.R., ed., Proceedings, 1976 Gulf Coast lignite conference: the University of Texas at Austin, Bureau of Economic Geology Rept. of Investigations No. 90, pp. 33-53.

______, 1978, Depositional systems in the Wilcox Group (Eocene) of east-central Texas and the occurrence of lignite, in Kaiser, W.R., editor, Proceedings, 1976 Gulf Coast lignite conference: The University of Texas at Austin, Bureau of Economic Geology Rept. No. 90, pp.33-53.

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

Klemt, W.B., Duffin, G.L., and Elder, G.R., 1976, Ground-water resources of the Carrizo aquifer in the Winter Garden area of Texas: Texas Water Devel. Board Rept. 210, v. 1 and 2, 30 pp. and 466 pp., respectively.

Kreitler, C.W., and others, 1980, Geology and hydrology of the east Texas Basin, a progress report of nuclear waste isolation feasibility studies (1979): The University of Texas at Austin, Bureau of Economic Geology Geological Circ. 80-12, 112 pp.

Larkin, T.J., and Bomar, G.W., 1983, Climatic Atlas of Texas: Texas Dept. of Water Resources LP 192, 151 pp.

McDonald, M.G., and Harbaugh, A.W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geol. Survey Open-File Rept. 83-875, 528 pp.

Meyer, W.R., and Carr, J.E., 1979, A digital model for simulation of ground-water hydrology in the Houston area, Texas: Texas Dept. of Water Resources LP 103, 27 pp.

Nichols, P.H., Peterson, G.E., and Wuestner, C.E., 1968, Summary of subsurface geology of northeast Texas: Am. Assoc. Petroleum Geologists Memoir 9, v. 20, pp.982-1004.

Pennequin, R.C., 1983, Ground-water flow model determinations of areal hydrogeology and geology: Ground Water, v. 21, no. 5, pp. 552-557.

Rogers, L.T., 1967, Availability and quality of ground water in Fayette County, Texas: Texas Water Devel. Board Rept. 56, 117 pp.

Texas Water Development Board, 1984, Water For Texas, A Comprehensive Plan for the Future, tow volumes: Texas Water Devel. Board GP-4-1, vol. 1, 72 pp., vol. 2, ? pp.

Texas Water Development Board, 1986, Surveys of Irrigation in Texas, 1958, 1964, 1969, 1974, 1979, and 1084: Texas Water Devel. Board Rept. 294,243 pp.

Thompson, G.L., 1966, Ground-water resources of Lee County, Texas: Texas Water Devel. Board Rept. 20, 131 pp.

Thorkildsen, D., and Price, R.D., 1987, Ground-Water Resources of the Carrizo-Wilcox Aquifer in the Central Texas Region: Texas Water Devel. Board Rept. in press, three volumes.

APPENDIX 1

PROCEDURE FOR DATA INPUT

Data, read directly from contour maps with the grid overlay, was input to a personal computer using dBase III plus software.

In dBase, the following eleven fields were set up; Row number, Column number, Layer number, Top of cell elevation, Bottom of cell elevation, Permeability of cell, Sand thickness in cell, Water level elevation in cell, Pumpage from cell, Drain conductance coefficient of cell, and Recharge to cell. All elevations are in feet above or below mean sea level. Permeability is in Gal/Day/SqFt. Sand thickness is in feet of sand for layers 1, 2, and 4 and in percent sand for layers 3 and 5. Pumpage and recharge are in cubic feet per second.

After all data had been input, an ASCII format file was created from dBase using the copy command with the SDF type option. This ASCII file, called LCRA1.TXT, is the input file to the preprocessor program called MODATA.

Program MODATA is a fortran program that prepares the data for input to the McDonald - Harbaugh model (MODFLOW) and prints out an optional data listing. The program reads the input data, calculates the necessary parameters, and writes the files (packages) to be read by the model. See the documentation within the source code of the program (MODATA.FOR) for more information.

The MODATA program is run by typing DATARUN at the prompt. The program then reads LCRA1.TXT and asks if a listing is wanted and whether the data will be for a steady-state or transient simulation with the number of stress periods. When the run is completed, four files will have been created; LBCF.11 (Block Centered Flow package), LBASIC.7 (Basic package), LDRAIN.14 (Drain package), and LPUMP.12 (Well package). The Well package includes pumpage and recharge. Block changes, if any, can be added at this time by using any ASCII text editor on the BCF package. Also, IBOUND values in the Basic package should be edited in order to have the desired constant heads. If the simulation is transient, the well package will have to be manually edited in order to include future pumpage scenarios.

There are three other packages, S.I.P., Output and River, that MODATA does not create. These are short and were easy to create with a text editor. The S.I.P package is called SIP.19, the Output package is called OUTPUT.13 and the River package is called LRIV.17.

APPENDIX 2

PROCEDURE FOR MODEL RUNS

Model runs were separated into three phases during this project: Phase 1 - steady-state simulations with constant heads in outcrop nodes (no recharge, drain package or river package); Phase 2 - steady-state simulations with recharge, river package and drain package included; and Phase 3 - transient simulations with future pumping and rainfall scenarios. Floppy diskettes with all the runs in the three phases are included with one copy of this report given to the L.C.R.A.

Phase 1

The purpose of Phase 1 was to calibrate the model by adjusting input parameters and/or structure as necessary to obtain the best possible simulated heads and flows.

Data for this phase was prepared in dBASE III using the LCRA1.DBF file. This file does not contain any recharge data as it was not required for phase 1 runs. Program MODATA was run with the file LCRA1.TXT (described in Appendix 1) in order to create necessary packages for input to the McDonald - Harbaugh Model. The other packages not created by MODATA (S.I.P. and Output) were created with an ASCII text editor.

To run the model type RUNLCRA at the prompt. The output from the model can be saved to a file instead of being printed out by modifying the RUNLCRA.BAT batch file. Run 1 is the calibrated Phase 1 run. The only change made to the original data for calibration was to increase the vertical hydraulic conductivity on a block of cells in layers 2 through 5. This was accomplished with block changes to VCONT values in the Block Centered Flow package (LBCF.11). See the model documentation (U2DREL module) for instructions on how to enter these block changes.

Phase 2

The purpose of this phase was to incorporate the drain package and river package in order to get an idea how much recharge enters and stays in the system.

Data for phase 2 is the same as for phase 1 except recharge has been added to the dBASE III file called LCRA2.DBF. Ten percent of the mean annual rainfall was input to the recharge field in every outcrop cell. Program MODATA was used to create a new Well package that includes both pumpage and recharge (file now called LPR10.12). Next, the Basic package was modified with a text editor to remove the constant heads from the outcrop nodes and to add the simulated heads from run 1 replacing the starting heads that MODATA creates. The River package was then created with a text editor. Then, the 13 nodes that are in the River package were removed from the Drain package. The other packages are the same as in run 1.

The model is run the same as before by typing RUNLCRA at the prompt. This produced run 2A (10 percent of the mean annual rainfall as recharge and run 1 final heads as starting heads).

Six more phase 2 runs were performed (runs 2B through 2G) for the purpose of adding a theoretical line of pumpage to all cells in row 13 in order to see if more effective recharge would remain within the system. The percentage of mean annual rainfall made available to the system was increased to 15 percent to insure there would be enough water to keep nodes from going dry in the early iterations. Run 2B was identical to run 2A except for the 15 percent recharge. Then, the run 2B final heads were used as starting heads for run 2C to verify that heads remained stable before we added the theoretical line of pumpage. The simulation section in the main text shows the amount of pumpage added to row 13 cells for runs 2D through 2G. The values are the percentages of mean annual rainfall that is pumped from each corresponding formation or layer.

The Well package was prepared for these runs by using Program MODATA after editing the dBase III file LCRAPUMP.DBF five different times entering the 15 percent recharge figures and the theoretical lines of pumpage. When using MODATA for creating only a Well package enter NUL for filenames of the other unit numbers so no other packages will be created or overwritten.

Phase 3

The purpose of Phase 3 was to apply prospective pumpage scenarios in a transient simulation of one or several stress periods in order to find out what kind of drawdowns can be expected. There are two Phase 3 runs supplied on floppy diskettes.

The first phase 3 run (Run 3A) is a 45 year transient simulation with one five year stress period and four ten year stress periods. The first stress period is five one year time steps simulating 1985 through 1989 using 1985 pumpage figures for the five time steps. The second stress period is ten one year time steps simulating years 1990 through 1999 using projected pumpage for year 1990 for the ten time steps. The third stress period simulates years 2000 through 2009 using projected pumpage for year 2000. The fourth stress period simulates years 2010 through 2019 using projected pumpage for year 2010 and the fifth stress period simulates years 2020 through 2029 using projected pumpage for year 2020.

Data for this Phase 3 run was created with Program MODATA with LCRA2.TXT specifying transient simulation and the number of stress periods. The same block changes as in run 1 were added to the newly created B.C.F. package. The final simulated heads from run 2A were added to the Basic package replacing the starting heads that MODATA creates. Also the variable PERLEN (the stress period time length) was changed. The Well package was built by using MODATA on four different dbase files

(LC1990.DBF, LC2000.DBF, LC2010.DBF, LC2020.DBF each edited with the projected pumpage pumpage figures) to create four different Well packages. Then, using the text editor, these four packages were merged into one with the original package creating the Well package with the five data sets needed.

The next Phase 3 run was a 16 year transient simulation with 16 one year stress periods (one time step per stress period) using run 2A final heads as starting heads (Run 3B). This run uses 2020 projected pumpage along with 1947 through 1961 precipitation data for a maximum stress situation. The first stress period uses normal precipitation with 2020 pumpage to stabilize the heads before the start of the 1947 stress period.

The data for this run was created with the same procedure as in the first phase 3 run. The Well package is a merge of 16 separate well packages using MODATA on 16 different dbase files (LC2020.DBF and LCRA47.DBF through LCRA61.DBF).

APPENDIX 3

SUMMARY OF RUNS SUPPLIED ON DISKETTES *

STEADY STATE

Run 1 -- Phase 1 run, verifies calibration of model. Run has constant heads in outcrop, no recharge or river and drain packages.

Run 2A -- Phase 2 run, used to incorporate recharge, river and drain packages. Run used run 1 final heads as starting heads and constant heads were removed from outcrop. Ten percent of mean annual rainfall was used for recharge.

Run 2B -- Phase 2 run, used for finding head changes when recharge is increased from 10 to 15 percent. Needed these heads for input to run 2C.

Run 2C -- Phase 2 run, checked to see if heads remained stable. Needed to have stable situation before runs 2D through 2G results could be meaningful.

Runs 2D through 2G -- Phase 2 runs, a line of theoretical pumpage was put in row 13 in order to see if effective recharge would be increased. See chart in phase 2 part of text for amount of pumpage added to the row for each formation.

TRANSIENT

Run 3A -- Phase 3 run, 45 year transient simulation (1985 through 2029) with five stress periods using final heads from run 1 as starting heads and five pumping schemes over the 45 years.

Run 3B -- Phase 3 run, 16 year transient simulation of 16 stress periods using 2020 projected pumpage figures with rainfall from the 1947 through 1961 period. The first stress period used normal rainfall to stabilize the heads. Starting heads were the final heads from run 2A.

* - Copies of these diskettes were provided only with Copy 1 of the report, which was given to the L.C.R.A. They may be viewed at the offices of the Texas Water Development Board, Suite 305, 611 S. Congress Ave., Austin, Texas.

APPENDIX 4

MCDONALD - HARBAUGH MODEL DOCUMENTATION *

Documentation for the U.S.G.S McDonald - Harbaugh model used in this project has been published by the U.S.G.S. entitled "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model" (U.S.G.S. Open-File Report 83-875). A copy of this documentation was included with copy 1 of this report given to the L.C.R.A..

This model was modified by the T.W.D.B in order to run on Personal Computers. The model as received from the U.S.G.S. was written in FORTRAN 66 and was converted to FORTRAN 77 by the T.W.D.B. so it could be compiled with the Microsoft FORTRAN version 4.01 compiler. Both versions of source code were included on floppy diskettes and given to the L.C.R.A. with this report.

Another modification to the T.W.D.B. version of the model was to add the capability of having cell by cell flow terms printed out. This was done in subroutine UBUDSV.FOR and is documented therein. Also, a page of instructions on how to use this change is inserted in the L.C.R.A.s' copy of the model documentation (page 154).

The compiled program included on the diskettes was compiled for a P.C. with a math co-processor and it is suggested that the program be run on a 80286 or 80386 P.C. with 640 kilobytes of main memory.

* - A copy of the model documentation was included only with Copy 1 of the report which was provided to the L.C.R.A. A copy may be viewed at the offices of the Texas Water Development Board, Suite 305, 611 S. Congress Ave., Austin, Texas. Copies are available from the U.S. Geological Survey.

APPENDIX 5

LIST OF FIGURES *

* - Copies of these figures were included only with copy 1 of the report which was provided to the L.C.R.A. They may be viewed at the offices of the Texas Water Development Board, Suite 305, 611 S. Congress Ave., Austin, Texas. A copy of Figure 1, Cross Section Locations A - A' through F - F', is included on page 2 of this Appendix, however.

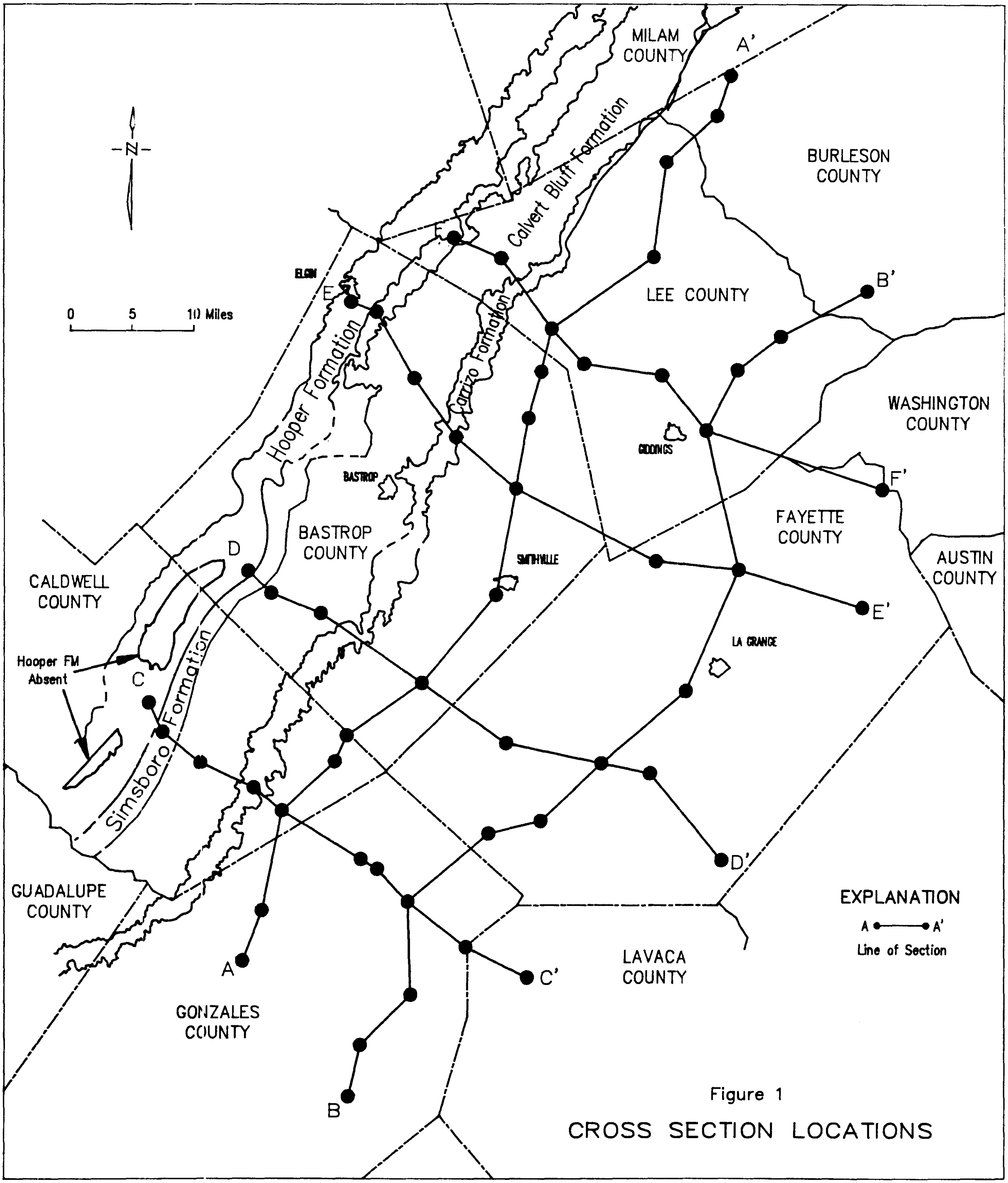

Figure 1

CROSS SECTION LOCATIONS